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REVIEW

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# Validity of activity monitors in health and chronic disease: a systematic review

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## Abstract

The assessment of physical activity in healthy populations and in those with chronic diseases is challenging. The aim of this systematic review was to identify whether available activity monitors (AM) have been appropriately validated for use in assessing physical activity in these groups. Following a systematic literature search we found 134 papers meeting the inclusion criteria; 40 conducted in a field setting (validation against doubly labelled water), 86 in a laboratory setting (validation against a metabolic cart, metabolic chamber) and 8 in a field and laboratory setting. Correlation coefficients between AM outcomes and energy expenditure (EE) by the criterion method (doubly labelled water and metabolic cart/chamber) and percentage mean differences between EE estimation from the monitor and EE measurement by the criterion method were extracted. Random-effects meta-analyses were performed to pool the results across studies where possible. Types of devices were compared using meta-regression analyses. Most validation studies had been performed in healthy adults ( $n = 118$ ), with few carried out in patients with chronic diseases ( $n = 16$ ). For total EE, correlation coefficients were statistically significantly lower in uniaxial compared to multisensor devices. For active EE, correlations were slightly but not significantly lower in uniaxial compared to triaxial and multisensor devices. Uniaxial devices tended to underestimate TEE ( $-12.07$  (95%CI:  $-18.28$  to  $-5.85$ ) %) compared to triaxial ( $-6.85$  (95%CI:  $-18.20$  to  $4.49$ ) %,  $p = 0.37$ ) and were statistically significantly less accurate than multisensor devices ( $-3.64$  (95%CI:  $-8.97$  to  $1.70$ ) %,  $p < 0.001$ ). TEE was underestimated during slow walking speeds in 69% of the lab validation studies compared to 37%, 30% and 37% of the studies during intermediate, fast walking speed and running, respectively. The high level of heterogeneity in the validation studies is only partly explained by the type of activity monitor and the activity monitor outcome. Triaxial and multisensor devices tend to be more valid monitors. Since activity monitors are less accurate at slow walking speeds and information about validated activity monitors in chronic disease populations is lacking, proper validation studies in these populations are needed prior to their inclusion in clinical trials.

**Keywords:** Chronic diseases, Doubly labelled water, Indirect calorimetry, Activity monitoring, Physical activity, Validation study, Systematic review

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## Systematic review

### Introduction

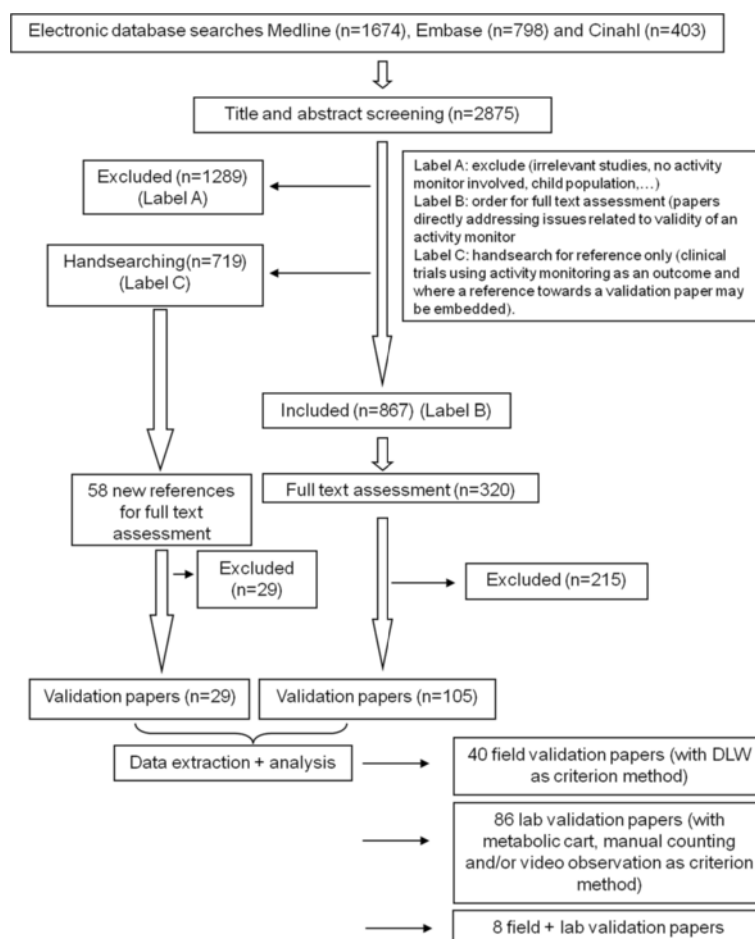
There is evidence that regular physical activity is associated with a reduced risk of mortality and contributes to the primary and secondary prevention of several chronic diseases [1]. For example, a reduced risk of coronary heart disease, cardiovascular disease, stroke and colon cancer has been reported in more active individuals [2]. In patients with chronic obstructive pulmonary disease (COPD), regular physical activity leads to a lower risk of both COPD related hospital admissions and mortality [3]. Physical activity limitation is a major problem in patients with chronic diseases and needs to be accurately measured if therapies aimed at improving this are to be properly evaluated. A range of devices are available for this purpose but most have been validated in young, healthy subjects and their applicability to older or unwell populations, where movements tend to be slower, is not well established.

Physical activity is defined as any bodily movement, produced by skeletal muscles, requiring energy expenditure

[4]. Daily physical activity can be considered as “the totality of voluntary movement produced by skeletal muscles during everyday functioning” [5]. Estimates of daily physical activity can be obtained by different approaches; questionnaires, energy expenditure measurements and activity monitors. Questionnaires rely on the subject’s recollection of activities and allow categorization of patients by physical activity (very active, active, sedentary and inactive) [6], but may lack the precision needed to detect changes in physical activity on a day to day basis.

Daily physical activity can be expressed as an overall measure of active energy expenditure, using indirect calorimetry techniques such as doubly labelled water or metabolic carts. Although doubly labelled water is regarded as a criterion method, this technique does not quantify the duration, frequency and intensity of physical activity performed. Metabolic cart systems which measure expired  $O_2$  and  $CO_2$  however cannot be used over extended periods of time.

Physical activity can also be monitored directly using physical activity monitors. In general, three classes of



**Figure 1** Flow chart describing the identification and inclusion of relevant studies.

**Table 1 Overview uniaxial activity monitors used in validation papers**

Name	Manufacturer	Field(F)/Lab(L) + reference	Size (and weight)	Placement	Cost	Epoch length	Data storage	Outcomes (measured)	Outcomes (calculated)
<b>Actigraph Model 7164 (formerly CSA, MTI)</b>	Actigraph LLC Pensacola, FL	F [14-24] + L [7,25-47]	5.1 x 4.1 x 1.5 cm (45.5 g)	hip, ankle or wrist	NA	5 s to 1 min.	22 days (1 min epochs)	AC, steps	EE, activity intensity level
<b>Actigraph Model GT1M</b>	Actigraph LLC Pensacola, FL	F [48-50] + L [29,49,51-57]	3.8 x 3.7x 1.8 cm (27 g)	hip, ankle or wrist	€239 (unit), €249 (software)	1 s to several minutes	378 days (1 min epochs)	AC, steps	EE, activity intensity level
<b>Caltrac</b>	Muscle Dynamics Fitness Network, Torrance, USA	F [58-62] + L [7,34,35,63-65]	7 x 7 x 2 cm	waist	€71 (unit)	NA	no data storage	AC	EE
<b>Kenz Lifecorder EX</b>	Suzuken Co Ltd., Nagoya, Japan	F [66,67] + L [51,68-70]	7.25 x 4.15 x 2.75 cm (40 g)	waist	€49 (unit) + €250 (software)	5 s to 10 min	200 days	Steps, activity level	EE, activity intensity level
<b>Calorie Counter Select II</b>	Suzuken Co Ltd., Nagoya, Japan	L [7,71]	5 x 3 x 1 cm	waist	NA	1 day	7 days	steps	EE
<b>ActivPAL</b>	PAL Technologies Ltd, Glasgow, UK	L [57,72-74]	5 x 3,5 x 0,7 cm (15 g)	midline on the anterior aspect of the thigh	NA	1 s to 1 min	10 days	Steps (cadence), different body positions, activity score	
<b>PALlite</b>	PAL Technologies Ltd, Glasgow, UK	L [74]	5 x 3.5 x 0.7 cm (20 g)	ankle	€239	1 s to 1 min	10 days	Steps	
<b>PAM model AM101B.V.</b>	Doorwerth, Netherlands	L [37]	5.8 x 4.2 x 1.3 cm (28 g)	waist	NA	1 s to 1 min.	3 months	PAM scores	
<b>Actiwatch</b>	Mini Mitter Co, Sunriver, OR, USA	L [75]	4.4 x 2.3 x 1 cm (16.1 g)	wrist	€713 (unit), €213 (reader)	15 s to 1 min	30 days (1 min epochs)	AC	
<b>Biotrainer</b>	IM Systems, Baltimore, MD, USA	L [41,64,76]	7x 7 x 2 cm (51.1 g)	hip	NA	NA	9 days	AC	EE
<b>Nike and iPod sensor</b>	Apple Inc, Cupertino, CA, USA	L [77]	2,4 x 3,5 x 0,8 cm (9 g)	shoe	€19 (sensor)	NA	16 GB	Ground contact time	Distance, speed, EE
<b>Polar Activity Watch 200</b>	Polar Electro Oy, Kempele, Finland	L [78]	NA	wrist	€152 (watch + software)	1 min	Up to 9 files	Steps, HR	EE, activity intensity level

Field study (F), lab study (L) or field + lab study (F + L). PAM; physical activity monitor, AC; activity counts, HR; heart rate, ECG; electrocardiogram, EE; energy expenditure, NA; not available, HR; heart rate.

activity monitors are being used increasingly in chronic disease populations (e.g. COPD): pedometers, accelerometers and integrated multisensor systems. Pedometers are devices which estimate the number of steps taken through mechanical or digital measurements in only the vertical plane. This is a limited measure of physical activity [7,8]. Accelerometers detect acceleration in one, two or three directions (uni-, bi- or triaxial accelerometers). These devices allow determination of the quantity and intensity of movements [9]. Integrated multisensor systems combine accelerometry with other sensors that capture body responses to exercise (e.g. heart rate or skin temperature) in an attempt to optimise physical activity assessments.

With the advancement of technology, the number of activity monitors available to measure physical activity is growing. However, despite these advances, it remains a challenge to assess physical activity in slowly moving patients (such as those with COPD, chronic heart failure and diabetes type II) [10-12]. In these patients small changes in physical activity are likely to be important effects of interventions aimed at enhancing physical activity. Therefore, in order for investigators to interpret the effect of interventions on physical activity, activity monitors that have been properly validated in these patient groups are needed.

In order to make evidence based statements on the validity of activity monitors, a systematic review was conducted to identify available activity monitors that have been validated in both healthy adults and chronic disease populations.

## Methods

### Inclusion criteria

Studies meeting the following criteria were included: (1) Population: healthy adults and adults with a diagnosis of chronic disease in whom inactivity is a likely contributor to morbidity or a target for treatment, but whose locomotor function is relatively preserved (COPD, heart

failure, diabetes type II, frail elderly, primary pulmonary hypertension, chronic low back pain, fibromyalgia syndrome, obesity). (2) Measurement: any commercially available activity monitor for outdoor activity monitoring from uniaxial to triaxial accelerometers and multisensor devices to tools incorporating spatial information (e.g. GPS) or other information on motion. (3) Study design: studies that evaluated the validity of an activity monitor, i.e. testing an activity monitor against a criterion method, such as indirect calorimetry. Two types of validation studies were included; field validation studies (validation of an activity monitor against doubly labelled water) and laboratory validation studies (validation of an activity monitor using a metabolic cart or metabolic chamber and/or manual step-counting or video observation). (4) Clinical trials using activity monitoring as an outcome and which might contain a reference to a validation paper were included for hand-searching. (5) A search window between 1<sup>st</sup> of January 2000 until 1<sup>st</sup> of March 2012 was selected in order to capture sensors in contemporary use. This approach still allowed for the identification of older validation studies (published before 2000) of devices in current use in clinical trials. Main exclusion criteria were 1) studies in children (subjects younger than 18 years), 2) studies in subjects with abnormal biomechanical movement patterns (e.g. cerebral palsy, lower limb amputation), 3) studies only investigating the number of steps using pedometers because of the inaccuracy in measurement of total energy expenditure [7] and lack of ability to measure physical activity patterns [8].

No language restrictions were used; any non-English studies retrieved through the literature search were translated to determine their appropriateness for inclusion.

### Search strategy and systematic review

Eligible studies were identified by searching the following databases: MEDLINE, EMBASE and CINAHL. A librarian was consulted prior to initiating the search in

**Table 2 Overview biaxial activity monitors used in validation papers**

Name	Manufacturer	Field(F)/Lab(L) + reference	Size (l x w x h) and (weight)	Placement	Cost	Epoch length	Data storage	Outcomes (measured)	Outcomes (calculated)
<b>Biotrainer Pro</b>	IM Systems, Baltimore, MD, USA	L [32]	7.6 x 5 x 2.2 cm (51.1 g)	hip	€142 (unit), €142 (software), €70 (cable)	15 s to 5 min	22 days (1 min epochs)	AC, steps, activity intensity level	EE
<b>Actitrac</b>	IM Systems, Baltimore, MD, USA	L [76]	5.6 x 3.8 x 1.3 cm (34 g)	wrist	€570 (unit), €285 (software), €70 (cable)	2 s to 2 min	44 days (1 min epochs)	AC	
<b>AMP-331</b>	Activity Monitoring Pod, Dynastream Innovations Inc., Cochrane, AB, Canada	L [26,38]	7,13 x 2,4 x 3,75 cm (50 g)	right ankle (directly over the Achilles tendon)	NA	1 min epochs	28 hours (1 min epochs), 3.5 days (3 min epochs)	steps, cadence, walking speed, stride length, distance	EE

Field study (F), lab study (L) or field + lab study (F + L). AC; activity counts, EE; energy expenditure, NA; not available.

**Table 3 Overview triaxial activity monitors used in validation papers**

Name	Manufacturer	Field(F)/Lab(L) + reference	Size (l x w x h) and (weight)	Placement	Cost	Epoch length	Data storage	Outcomes (measured)	Outcomes (calculated)
<b>Actigraph GT3x</b>	Actigraph LLC Pensacola, FL	L [79]	4.6 x 3.3 x 1.5 cm (19 g)	Hp, ankle or wrist	€936 (device + software)	1 s to 1 min	19 days	VMU, steps	EE, activity intensity level
<b>RT3- Research Tracker</b>	Stayhealthy Inc. Monrovia, CA	F [80,81] + L [32,38,54,55, 80,82,83]	7.1 x 5.6x 2.8 cm (65.2 g)	hip or waist	€142 per unit, €214 for docking station	1 s to 1 min	21 days	AC, VMU	EE
<b>TriTrac R3D</b>	Hemokinetics Inc, Madison, WI	F [14,16,80] + L [31-33,41,63, 75,80,82,84-86]	10.8 x 6.8 x 3.3 cm (170.4 g)	waist	\$500	1 min	14 days	AC, VMU	EE
<b>Tracmor</b>	Philips Research, Eindhoven, The Netherlands	F [87-94] + L [95-97]	7.2 x 2.6x 0.8 cm (22 g)	waist	€142 per unit, €214 for docking station	NA	21 days	AC	EE
<b>Tracmor<sub>D</sub> (Philips DirectLife)</b>	Philips New Wellness Solutions	F [98]	3,2 x 3,2 x 0,5 cm (12,5 g)	Lower back	€113	NA	22 weeks	AC	EE
<b>Dynaport activity monitor</b>	McRoberts BV, The Hague, The Netherlands	F [99]	12.5 x 9.5 x 3 cm (375 g)	waist + one leg sensor (thigh)	€4900 (+software)	1 s to 1 min	2 days (continuously) More days if SD memory card is used	movement intensity, different body positions	
<b>Dynaport minimod</b>	McRoberts BV, The Hague, The Netherlands	L [100,101]	8.5 x 5 x 1 cm (70 g)	waist	€1500 (unit)	1 s to 1 min	7 days	movement intensity, different body positions, steps	EE
<b>Biotel 3dNx</b>	Biotel Ltd, Bristol, UK	F [102] + L [29,103]	12.5 x 5.8 x 0.8 cm	hip or waist	€800	5 s to 60s	700 days	VMU	EE
<b>Actimarker, EW4800P</b>	Panasonic Electric Works Co Ltd, Osaka, Japan	F [67]	6 x 3.5 x 1.3 cm (24 g)	waist	€86 (device)	1 min	180 days	VMU	EE
<b>ActivTracer</b>	GMS, Tokyo, Japan	L [104]	4.8 x 6.7 x 1.6 cm (57 g)	waist				VMU	EE, activity intensity level
<b>Actical</b>	Mini Mitter Co, Sunriver, OR, USA	F [105] + L [26,38,44, 54,106-112]	2.8 x 2.7 x 1.0 cm (17.5 g)	hip, ankle or wrist	€678 (incl. software)/ €321 (unit)	15 s to 1 min.	45 days (1 min epochs)	AC, steps	EE, activity intensity level
<b>e-AR (earworn activity recognition sensor)</b>	Sensixa Ltd, London, UK	L [113]	5,6 x 3,5 x 1,0 cm (7,4 g)	ear	NA	1 min	NA	AC	EE
<b>PASE (Physical Activity Sensing Earpiece)</b>	MMA7260Q, Freescale Semiconductor, Austin, Texas	L [114]	0,6 x 0,6 x 0,14 cm (40 g, including data logging system)	ear	NA	15 s to 1 min.	NA	Acceleration units	EE, activity intensity level
<b>GENEA</b>	Unilever Discovery, Sharnbrook Bedfordshire, UK	F [115] + L [55]	3,6 x 3,0 x 1,2 cm (16 g)	Wrist, waist, ankle	NA	NA	8 days	VMU	EE
<b>Activity Style Pro HJA-350IT</b>	Omron Healthcare, Kyoto, Japan	L [116]	7.4 x 4.6 x 3.4 cm (60 g)	waist	NA	NA	NA	VMU	Activity intensity level
<b>CAM (Continuous Activity Monitor)</b>	Maastricht Instruments B.V.	L [117]	6.3 x 4.5 x 1.8 (102 g)	leg	NA	NA	NA	VMU	Activity intensity level, Different body positions

Field study (F), lab study (L) or field + lab study (F + L). AC; activity counts, VMU; vector magnitude units, EE; energy expenditure, NA; not available.

**Table 4 Overview multisensor activity monitors used in validation papers**

Name	Manufacturer	Field(F)/Lab(L) + reference	Size (l x w x h) and (weight)	Placement	Cost	Epoch length	Data storage	Outcomes (measured)	Outcomes (calculated)
<b>PAMS (Physical Activity Monitoring System)</b>	ICSensors 3031-010, Druck, The Netherlands	L [118]	5,0 x 3,0 x 0,8 cm (Tracmor, 16 g) + 4 tilt sensors (total weight = 1,3 kg)	lower back (Tracmor) + lateral aspect of the trunk and to the lateral aspect of the mid-thigh (sensors)	NA	NA	NA	voltage units	body position (lying, sitting, standing)
<b>Actireg</b>	Premed AS, Oslo, Norway	F [119,120] + L [46]	8,5 x 4,5 x 1,5 cm (60 g)	waist (storage unit) + chest and right thigh (sensors)	€440 (device) + €380 (software)	1 s to 1 min	30 days	body position and movement	Activity intensity level, EE
<b>Vitaport (+ 4 uniaxial accelerometers (ADXL202))</b>	University of Cologne, Cologne, Germany (Vitaport)/Analog devices, Breda, The Netherlands (Uniaxial accelerometers)	L [121]	1,5 x 1,5 x 1 cm (uniaxial accelerometer, 8 g)/6 x 11 x 3 cm (Vitaport, data recorder, 500 g)	4 sensors: 2 on skin of the ventral side of each thigh, 2 on the skin of the sternum,	€ 15.000	1 s to 1 min	3 days	acceleration units	motility legs, motility trunk, motility body
<b>Sensewear Pro Armband (formerly Healthwear Armband)</b>	Bodymedia, Pittsburgh, PA, USA	F [50,122-126] + L [32,46,100, 125-138]	8,8 x 5,6 x 2,1 cm (82 g)	Upper right arm at triceps (midhumerus point)	€800 (device) + €1597 (software)	1 min	14 days	Steps, activity intensity level	EE
<b>SenseWear Mini Armband</b>	Bodymedia, Pittsburgh, PA, USA	F [124]	NA	Upper left arm at triceps (midhumerus point)	€722 (device) + €1597 (software)	1 s to 1 min	28 days	Steps, activity intensity level	EE
<b>Actiheart</b>	Mini Mitter Sunriver, OR, USA	L [29,108,139]	0,5 x 1,1 x 2,2 cm (clip) + 10 cm (wire) (10 g)	3th intercostals space (clip) + 2 ECG electrodes (chest)	€1330	15 s to 1 min	11 days (1 min epochs)	Acceleration HR, HR variability, ECG amplitude	EE
<b>Ikcal</b>	Teltronic AG, Biberist, Switzerland	L [46]	NA	Chest (elastic belt around the sternum)	NA	NA	NA	Acceleration, HR	EE
<b>Multi-sensor board</b>	Department of Epidemiology, University of Washington, USA	L [111]	25 g	Hip	NA	1 s to 1 min	NA	Steps, activity intensity level, different body positions	EE
<b>IDEEA (Intelligent Device for Energy Expenditure and Activity)</b>	MiniSun, LLC, Fresno, CA, USA	F [140] + L [141]	7 x 5,4 x 1,7 cm (59 g) (recorder) + 1,8 x 1,5 x 0,3 cm (2 g) (sensor)	Waist (processing unit) + sole of both feet, both thighs and chest (sensors)	NA	1 s to 1 min	7 days	Activity code, speed, distance, power output	EE

Field study (F), lab study (L) or field + lab study (F + L). AC; activity counts, EE; energy expenditure, NA; not available.

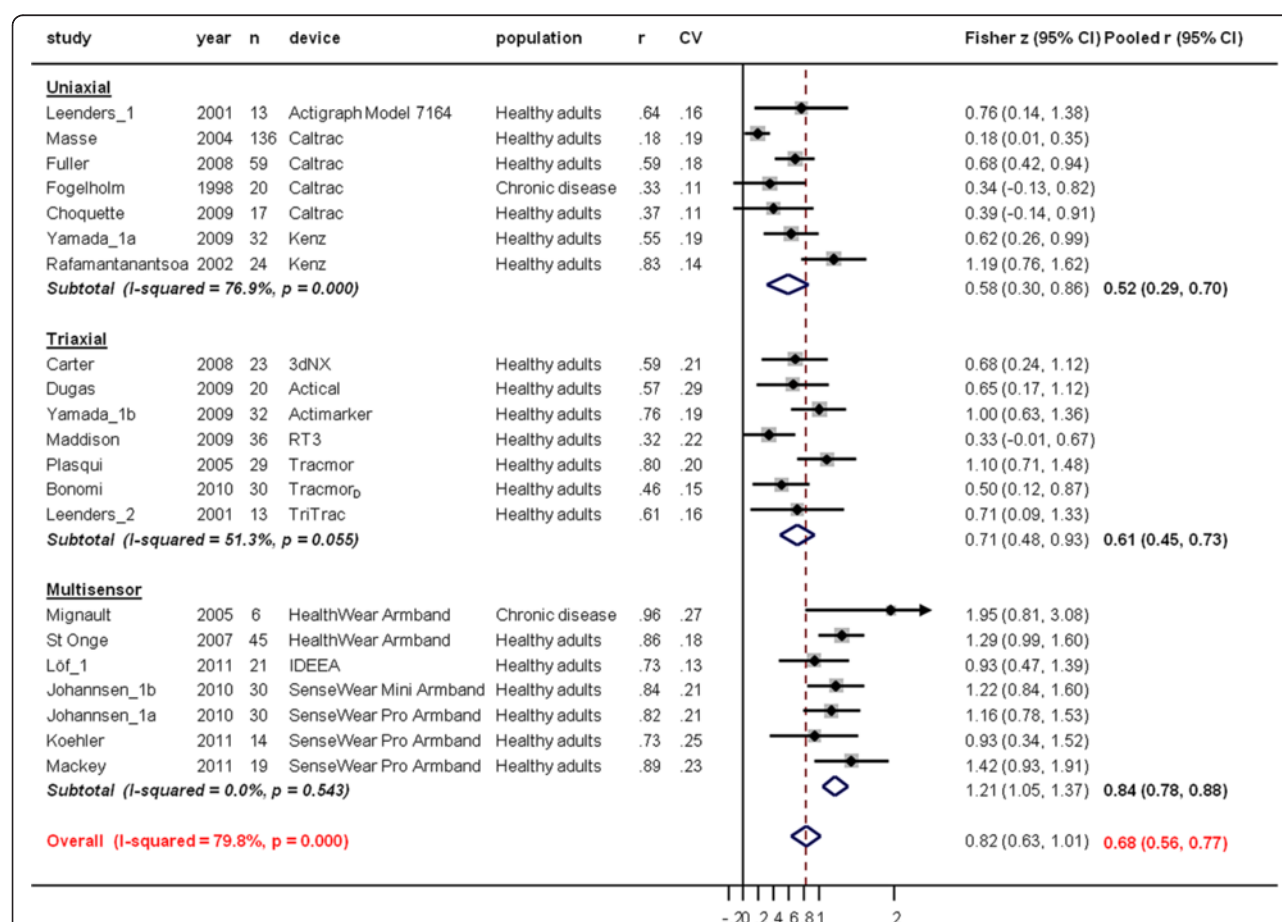


order to identify appropriate search terms to describe the population (from healthy adults to patients with chronic disease), physical activity and activity monitoring. A combination of MeSH terms (MEDLINE), Emtree terms (Embase) and Cinahl headings (Cinahl) with free text words (all databases) were used (see Additional file 1 for detailed information). Refworks (www.refworks.com) was used to store and share all papers and to collect all the information of title and abstract screening, full text assessment and the hand-searching process. Each review team consisted of 3 reviewers who independently screened the titles and abstracts of the retrieved articles. Each abstract was labelled as 'A) excluded papers', 'B) order for full text assessment' or 'C) hand-search for references only', i.e. clinical trials which may have a reference to an older validation study. After independently reviewing the articles for inclusion, the reviewers compared their labels to ensure consensus. Once agreement had been reached, a full text copy of

each article that met the inclusion criteria was obtained (Label B). Thereafter, the same review teams looked at the full texts of the potential validation papers in detail and decided in consensus, whether the articles were indeed suitable validation papers for data extraction. Subsequently, hand-searching of the clinical trials using an activity monitor outcome which might contain a reference to a validation paper (Label C), was performed by three independent reviewers. After independently reviewing these full texts, validation papers were identified which met the inclusion criteria for full text assessment. Again, the reviewers compared their decisions to ensure consensus. Data of all included validation papers were extracted into predefined prepared Excel tables.

### Data extraction

For the field studies, correlation coefficients between total and active energy expenditure from activity monitor ( $TEE_{AM}$  and  $AEE_{AM}$  respectively) and total



**Figure 2 Study-specific correlation coefficients (r) and Fisher z-scores (diamond) between total energy expenditure estimate from the activity monitor ( $TEE_{AM}$ ) and total energy expenditure measure from doubly labelled water ( $TEE_{DLW}$ ).** Each dot represents the z-score of the respective study together with a 95% confidence interval (CI) and the size of the box represents the weight of the study in the meta-analysis. Weights are from random effects analysis. CV; coefficient of variation for  $TEE_{DLW}$ .



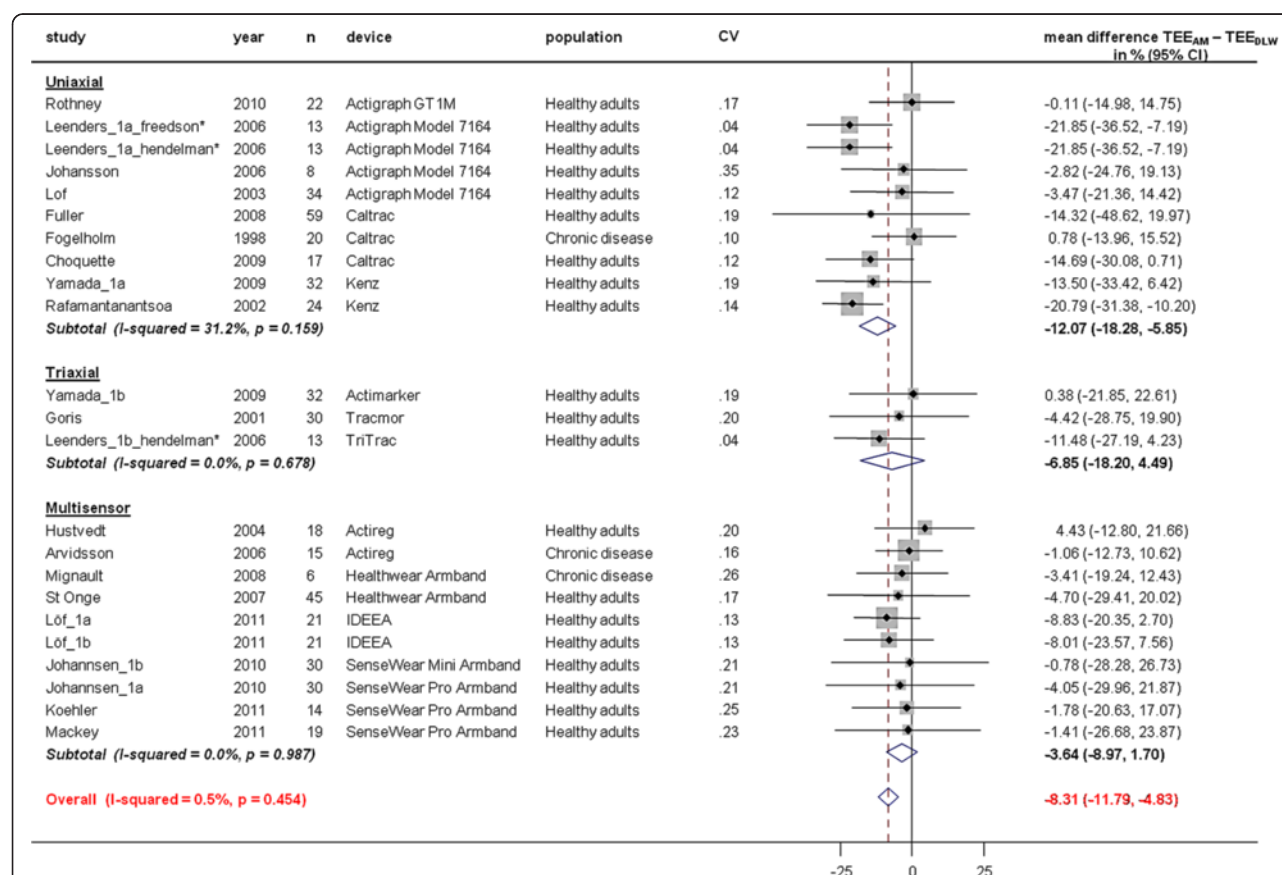
and active energy expenditure measured with doubly labelled water ( $TEE_{DLW}$  and  $AEE_{DLW}$  respectively) were extracted. The percentage mean differences ( $\Delta TEE$  and  $\Delta AEE$ ) with 95% confidence intervals were obtained from the reports to assess agreement between energy expenditure estimates from the activity monitor ( $TEE_{AM}$  and  $AEE_{AM}$ ) versus energy expenditure measures from doubly labelled water ( $TEE_{DLW}$  and  $AEE_{DLW}$ ). For the laboratory studies, correlation coefficients between activity monitor outcome and EE measured by metabolic cart/chamber were extracted. A sub-analysis included to compare correlation coefficients derived from walking based protocols to correlation coefficients derived from protocols based on activities of daily living. Agreement between energy expenditure outcomes from the activity monitor versus criterion method (indirect calorimetry) were extracted by the mean difference at different treadmill walking speeds; slow walk (<3.2 km/hr or 1 mph), intermediate speed walk (3.2-6.4 km/hr or 2-4 mph), fast walk (6.5-

8.05 km/hr or 4-5 mph) and running (8.06-11 km/hr or 5-7 mph). Accuracy of steps measured by activity monitoring was expressed as the percentage mean difference between steps measured by an activity monitor versus actual steps measured by the criterion method (video observation and/or manual step counting).

### Statistical analysis

Descriptive statistics were used to report information about type of activity monitor, activity monitor outcomes and studied population. Papers were separated by type of validation, 'field validation papers' (validation of an activity monitor against indirect calorimetry, using the doubly labelled water technique) and 'lab validation papers' (validation of an activity monitor against indirect calorimetry, using a metabolic cart, metabolic chamber or direct observation).

We also analysed the results separately per type of device (uni-, bi-, triaxial and multisensor devices). We performed (DerSimonian and Laird) random-effects meta-



**Figure 3 Study-specific % mean difference (diamond) between total energy expenditure estimate from the activity monitor ( $TEE_{AM}$ ) and total energy expenditure measure from doubly labelled water ( $TEE_{DLW}$ ).** Each dot represents the mean difference of the respective study together with a 95% confidence interval (CI) and the size of the box represents the weight of the study in the meta-analysis. Weights are from random effects analysis. CV; coefficient of variation for  $TEE_{DLW}$ . \*Leenders et al. 2006 (Actigraph Model 7164);  $TEE_{AM}$  estimated with most frequently used Freedson and Hendelman equation (walking outdoors), (not reported) data of % mean difference ( $\pm$ SD) between  $TEE_{AM} - TEE_{DLW}$  with other previously published equations can be found in the original paper [14].

analyses to pool the correlation coefficients and mean differences across studies and expressed heterogeneity by the  $I^2$  statistic, which estimates the percentage of total variation between studies that is due to heterogeneity rather than chance.  $I^2$  is calculated from basic results obtained from a typical meta-analysis as  $I^2 = 100\% \times (Q - df) / Q$ , where  $Q$  is Cochran's heterogeneity statistic and  $df$  the degrees of freedom. Negative values of  $I^2$  are put equal to zero so that  $I^2$  lies between 0% en 100% with larger values showing larger heterogeneity. We used the Fisher  $r$  to  $z$ -transformation in order to pool normally distributed data ( $z$  scores) rather than the skewed distribution of Pearson correlation coefficients [13]. We back transformed the pooled  $z$ -scores to correlation coefficients for easier interpretation.

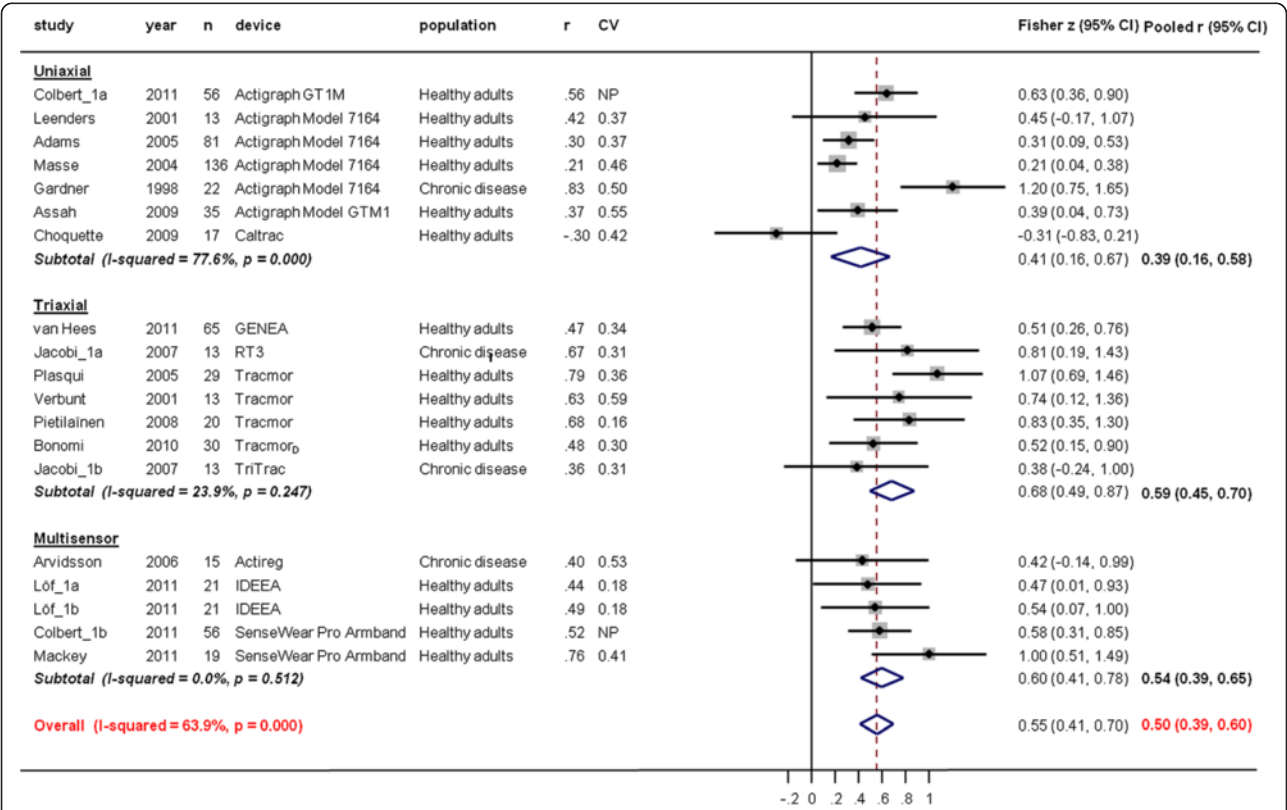
We used random-effects linear regression models (meta-regression analyses) with the studies' results as the dependent variable (and considering each studies' standard error) to compare the type of devices (covariate) and to assess the type of population (covariate) as a potential explanation for heterogeneity. For those few studies where no measures of variability were reported we imputed the median standard deviations of those

studies where the standard deviation was available. We did not perform meta-analyses for the laboratory studies where none of the studies provided standard deviations for  $\Delta TEE$  and  $\Delta AEE$  but presented the point estimates as graphs. Coefficient of variation for  $TEE_{DLW}$  and  $AEE_{DLW}$  was calculated per study population to investigate whether the degree of variation in  $TEE_{DLW}$  and  $AEE_{DLW}$  affected the correlation coefficients and/or mean differences, (i.e. higher correlations/mean differences in populations with larger variation in  $TEE$  and/or  $AEE$ ).

Results

The systematic literature search resulted in a total of 2875 abstracts which were scrutinised by four review teams across Europe. Figure 1 represents the different processes used in the systematic review.

Forty monitors were tested in validation studies; 12 uniaxial, 3 biaxial, 16 triaxial accelerometers and 9 multisensor devices. Fifty-five percent of activity monitors (22/40) were used only in lab validation studies, 10% (4/40) only in field validation studies and 35% (14/40) in both a lab as well as a field validation study. An



**Figure 4** Study-specific correlation coefficients and Fisher z-scores (diamond) between active energy expenditure estimate from the activity monitor (AEE<sub>AM</sub>) and active energy expenditure measure from doubly labelled water (AEE<sub>DLW</sub>). Each dot represents the z-score of the respective study together with a 95% confidence interval (CI) and the size of the box represents the weight of the study in the meta-analysis. Weights are from random effects analysis. CV; coefficient of variation for AEE<sub>DLW</sub>.

overview of the different activity monitors is shown in Tables 1, 2, 3 and 4.

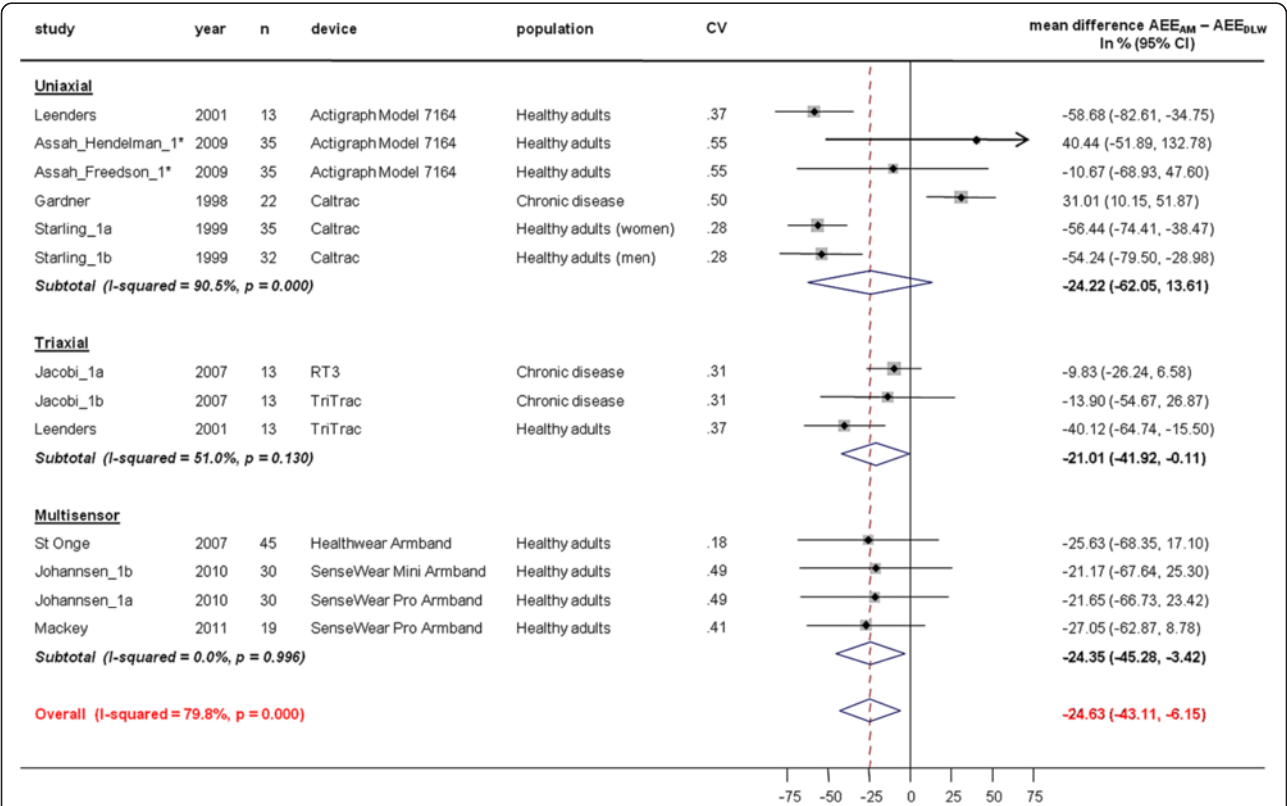
The most frequently available outcomes present in validated activity monitors are (total and/or active) energy expenditure (70%, 28/40), steps (38%, 15/40) and different levels of physical activity intensity (38%, 15/40). The majority of the validation studies (118/134, 88%) were performed in healthy adults. Few studies (16/134, 12%) were performed in chronic disease populations; obesity (n=4), chronic obstructive pulmonary disease (n=5), chronic heart failure (n=1), chronic organ failure (n=1), chronic low back pain (n=1), fibromyalgia syndrome (n=1), peripheral arterial disease (n=1), diabetes mellitus type II (n=1) and a general chronic disease population (cardiac, obese or knee arthritis, n=1).

Field validation studies

Individual correlation coefficients, with converted Fisher z-scores, for total energy expenditure (TEE) between TEE<sub>AM</sub> and TEE<sub>DLW</sub> are presented in Figure 2.

Variability of study populations' TEE<sub>DLW</sub> was relatively small; coefficient of variation (CV) ranged from 0.11 to 0.29. Pooled r in uniaxial devices (r = 0.52 (95%CI, 0.29 to 0.70)) was significantly lower compared to multisensor devices (r = 0.84 (95%CI, 0.78 to 0.88), p<0.001) but not to triaxial devices (r = 0.61 (95%CI, 0.45 to 0.73, p = 0.37)). Because of the relatively large difference in accuracy between the uniaxial, the triaxial and multisensor devices 53% of the between-study heterogeneity was accounted for by type of device in meta-regression analyses.

ΔTEE (TEE<sub>AM</sub> – TEE<sub>DLW</sub>) was less accurate in uniaxial compared to triaxial accelerometers and multisensor devices (–12.07 (95%CI, –18.28 to –5.85) % in uniaxial versus –6.85 (95%CI, –18.20 to 4.49) % in triaxial (p = 0.39 for comparison against uniaxial devices) and –3.64 (95%CI, –8.97 to 1.70) % in multisensor devices, p = 0.03 for comparison against uniaxial devices, Figure 3). ΔTEE were smaller in studies with chronic disease populations than in studies with healthy populations (–9% (95%CI –19 to 1)) but the difference did not reach statistical significance (p = 0.09).



**Figure 5 Study-specific % mean difference (diamond) between active energy expenditure estimate from the activity monitor (AEE<sub>AM</sub>) and total energy expenditure measure from doubly labelled water (AEE<sub>DLW</sub>).** Each dot represents the mean difference of the respective study together with a 95% confidence interval (CI) and the size of the box represents the weight of the study in the meta-analysis. Weights are from random effects analysis. CV; coefficient of variation for AEE<sub>DLW</sub>. \*Assah et al. 2009 (Actigraph Model 7164); AEE<sub>AM</sub> estimated with most frequently used Freedson and Hendelman equation, (not reported) data of % mean difference between AEE<sub>AM</sub> – AEE<sub>DLW</sub> with other data derived and previously published equations can be found in the original paper [48].

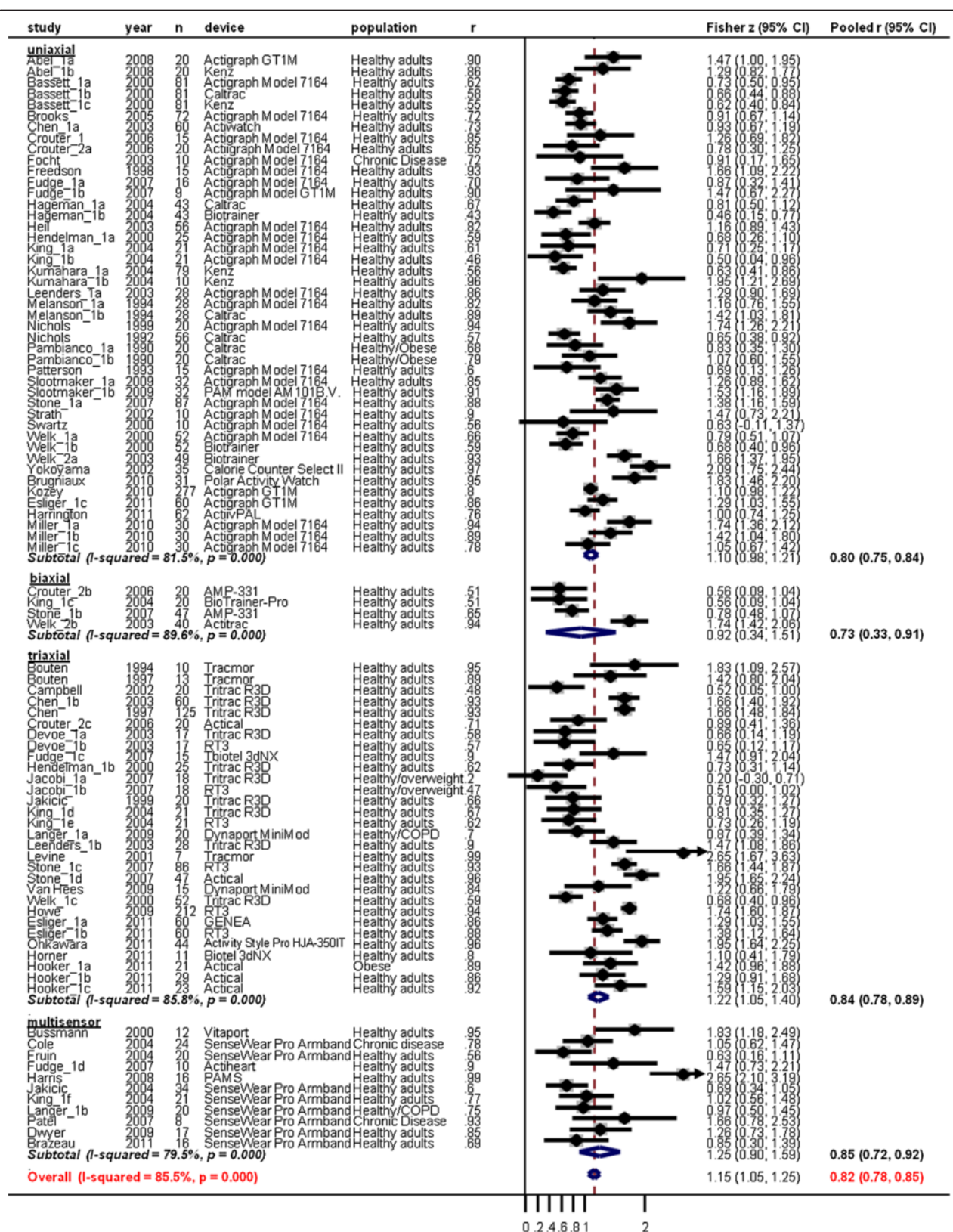


Figure 6 (See legend on next page.)



(See figure on previous page.)

**Figure 6 Study-specific correlation coefficients ( $r$ ) and Fisher z-scores (diamond) between activity monitor outcomes and total energy expenditure measure from indirect calorimetry ( $TEE_{IC}$ ) during laboratory protocols.** Each dot represents the z-score of the respective study together with a 95% confidence interval (CI) and the size of the box represents the weight of the study in the meta-analysis. Weights are from random effects analysis.

Correlations for active energy expenditure (AEE) between  $AEE_{AM}$  and  $AEE_{DLW}$  were higher in triaxial (0.59 (95%CI, 0.45 to 0.70)) and multisensor devices (0.54 (95%CI, 0.39 to 0.65)) compared to uniaxial (0.39 (95%CI, 0.16 to 0.58)) devices,  $p=0.12$  for triaxial and  $p=0.32$  for multisensor against uniaxial devices) (Figure 4) Types of devices accounted for only 12% of the between-study heterogeneity in the meta-regression analysis. All monitors underestimated AEE ( $\Delta AEE$  ( $AEE_{AM} - AEE_{DLW}$ ) -24.22 (95%CI, -62.05 to -13.61) % in uniaxial, -21.01 (95%CI, -41.92 to -0.11) % in triaxial and -24.35 (95%CI, -45.28 to -3.42) % in multisensor devices. No significant differences were found between devices (Figure 5). But  $\Delta AEE$  were statistically significantly smaller in studies with chronic disease populations than in studies with healthy populations (-44%, 95%CI -73 to -13,  $p=0.006$ ).

#### Laboratory validation studies

For correlation analysis, TEE and AEE, as determined from indirect calorimetry, were used as criterion outcomes (in 89% and 11% of the studies, respectively) against different outcomes of the activity monitor (activity counts (37%), vector magnitude units (7%), total energy expenditure (48%), active energy expenditure (2%) or monitor-specific activity scores (6%).

Pooled correlation coefficients between indirect calorimetry ( $TEE_{IC}$ ) and activity monitor outcome were lower in uniaxial (0.80 (95%CI, 0.75 to 0.84)) compared to multisensor devices (0.85 (95%CI, 0.72 to 0.92)) but the difference did not reach statistical significance ( $p=0.43$ ) No differences were found with biaxial (0.73 (95%CI, 0.33 to 0.91),  $p=0.50$ ) and triaxial (0.84 (95%CI, 0.78 to 0.89),  $p=0.28$ ) devices, either (Figure 6).

Correlation coefficients between  $TEE_{IC}$  and activity monitor outcome were higher when tested using laboratory protocols based on walking activities (overall pooled  $r=0.84$  (95%CI, 0.79 to 0.87), no significant differences between types of devices, Figure 7) compared to protocols using activities of daily living involving the upper and lower limbs (overall pooled  $r=0.75$  (95%CI, 0.68 to 0.81, no significant differences between types of devices), Figure 8).

There was evidence of heterogeneity of results across all analyses (overall  $I^2$  ranged from 84.6% (Figure 7) to 85.9% (Figure 8)). Again, the results did not differ for

chronic disease and healthy populations in any of the analyses on laboratory validation studies.

Mean differences between  $TEE_{AM}$  and  $TEE_{IC}$  at different treadmill walking speeds are presented in Figures 9, 10, 11 and 12. TEE was underestimated during slow walking speed in 69% of studies ( $n=16/23$ ), whereas in only 37% of studies ( $n=15/40$ ) during intermediate walking speed, 30% of studies ( $n=10/33$ ) during fast walking speed and 37% of studies ( $n=7/19$ ) during running reported underestimation of TEE. Underestimations in the slow walking group were relatively larger.

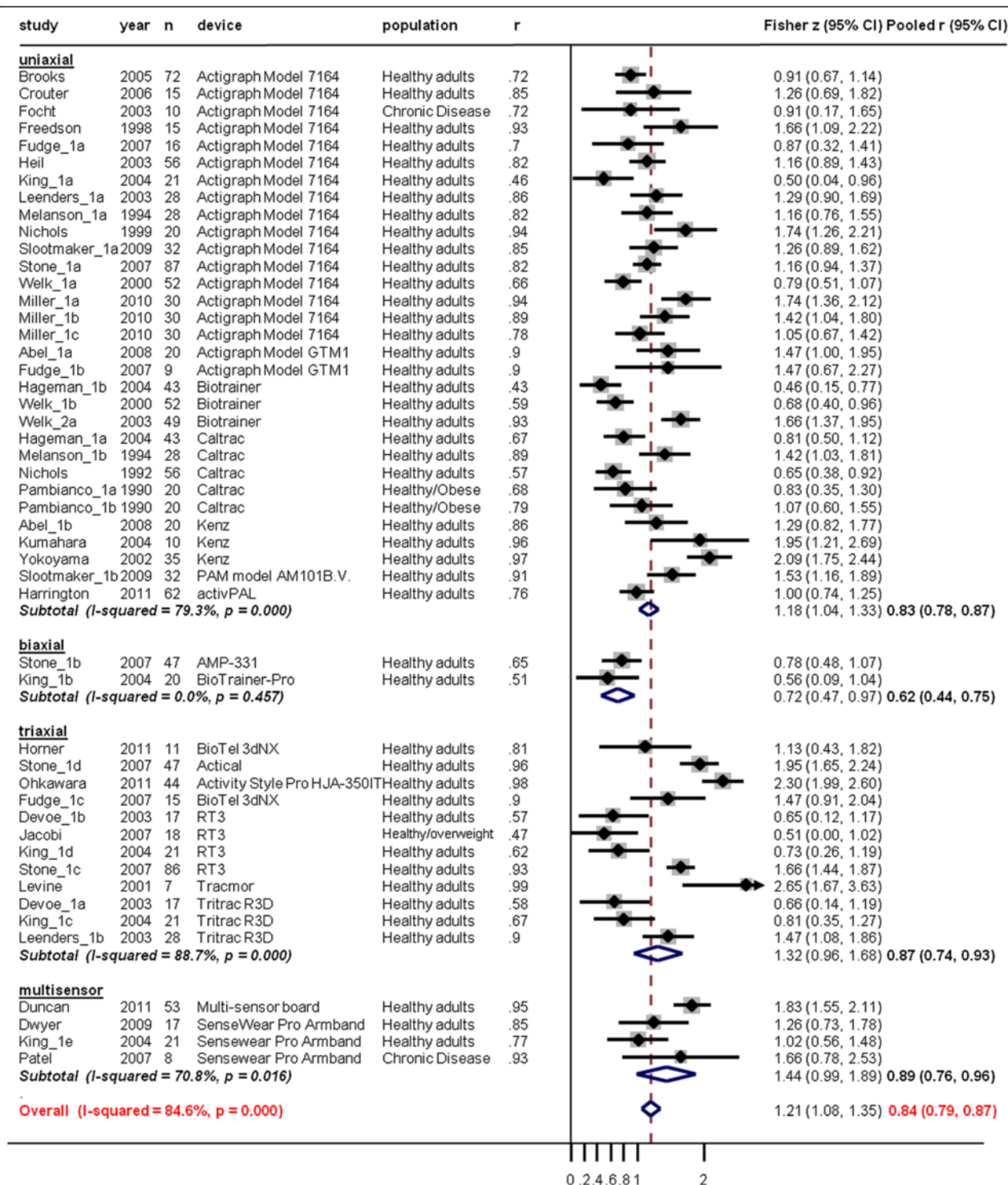
All accelerometers underestimate steps during slow walking; from 0.94 to 60% underestimation. One uniaxial device (activPAL), mounted on the thigh, showed a high accuracy in measuring steps during slow walking with only 0.94% overestimation. More accurate estimates of steps were reported at higher speeds; from 13% under to 2% overestimation during intermediate walking speed (except one study with 35% underestimation using SenseWear Armband), and from 0.18 to 4.3% overestimation during fast walking (Figure 13).

#### Discussion

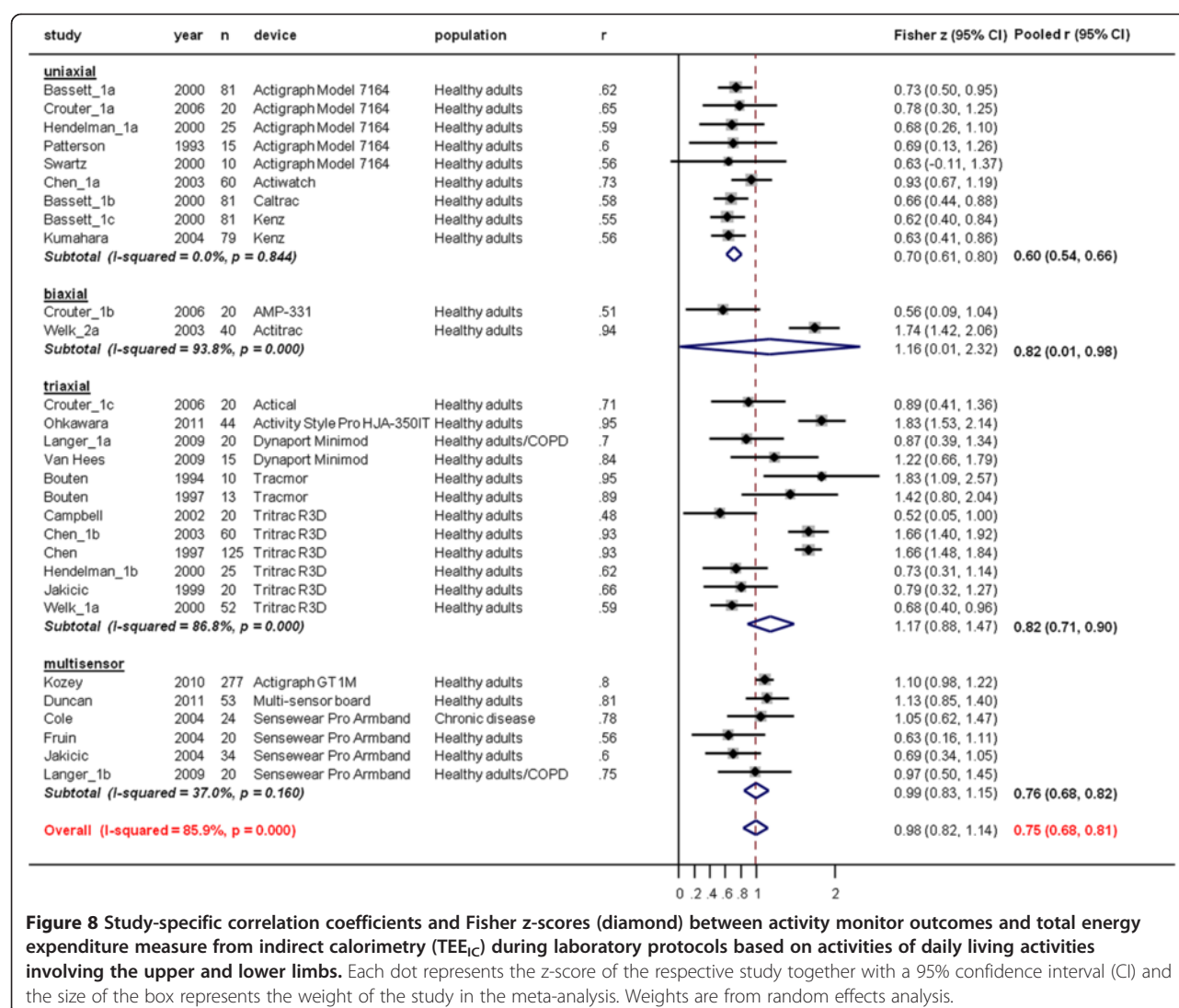
This systematic review of the literature identified forty activity monitors (12 uniaxial, 3 biaxial, 16 triaxial and 9 multisensor devices) that had been validated against indirect calorimetry (doubly labelled water, metabolic cart and/or metabolic chamber) in healthy adults (88% of studies) or adults with chronic disease (12% of studies).

Field and laboratory validation studies had highly heterogeneous results which could partly be explained by the type of activity monitor and the activity monitor outcome. These factors need consideration when a validation study is evaluated.

First, selecting the type of activity monitor is important. Pedometers are limited in their ability to detect certain physical activity patterns which might occur in chronic disease populations (for example, an unstable gait profile or lack of intensity of physical activity). Accelerometers can overcome this. Multi-axial accelerometers have the ability to measure accelerations in different orientations, which provides information about the total amount, intensity and duration of daily physical activity. Some multisensor devices, which combine



**Figure 7** Study-specific correlation coefficients and Fisher z-scores (diamond) between activity monitor outcomes and total energy expenditure measure from indirect calorimetry ( $TEE_C$ ) during laboratory protocols based on walking activities. Each dot represents the z-score of the respective study together with a 95% confidence interval (CI) and the size of the box represents the weight of the study in the meta-analysis. Weights are from random effects analysis.



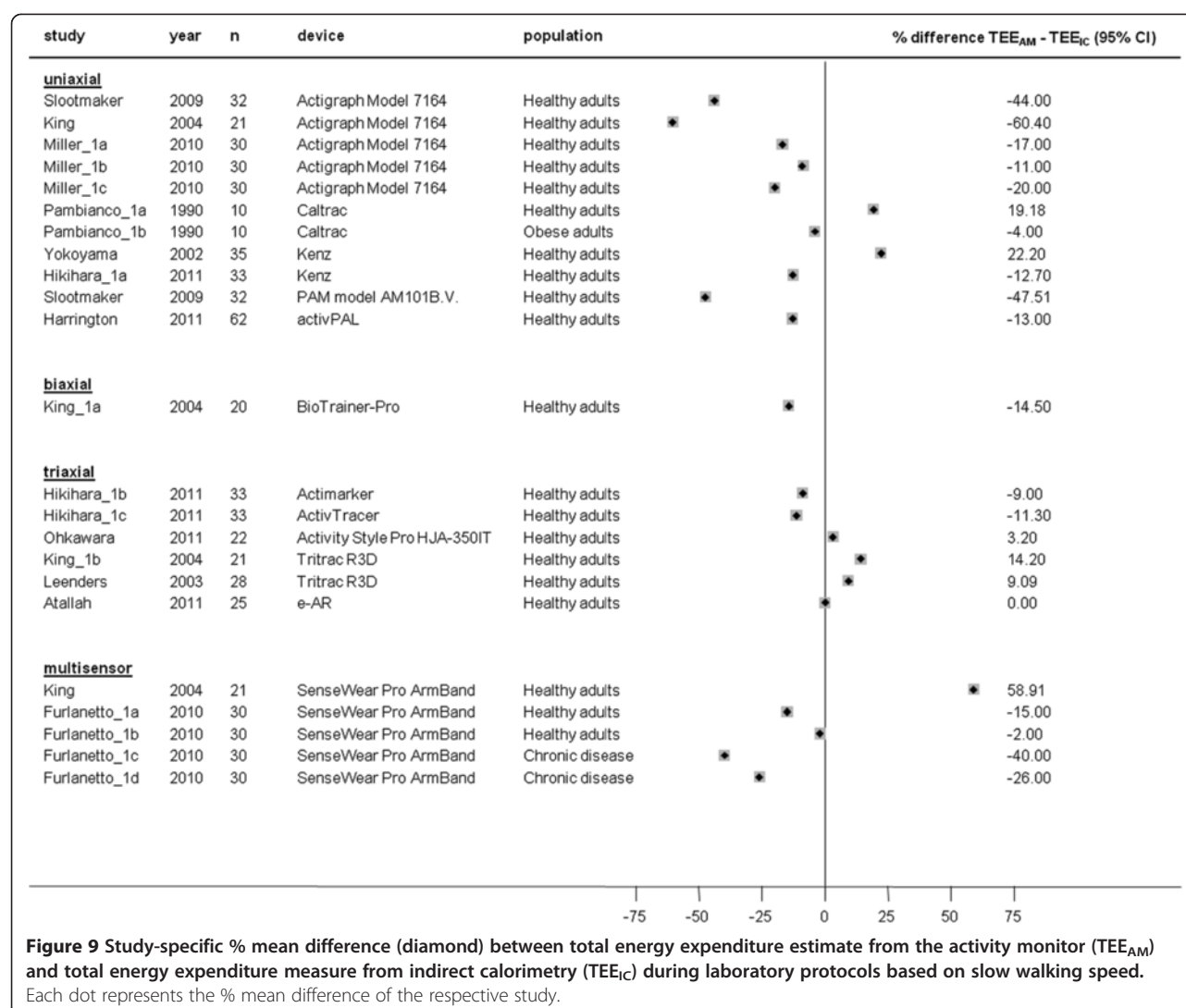
physiological parameters with accelerometry, are available to assess both body posture and body movement. An additional promising class of monitors integrate positioning systems (Global Positioning System (GPS) and Bluetooth® systems for outdoor and indoor activities respectively) with accelerometry and other sensors. However, to date, these have been used infrequently in patients with chronic disease [142,143]. Based on this systematic review, heterogeneity among studies was significantly explained by the types of devices, although no statistical significance was reached between different types of devices.

A second factor to take into consideration is the activity monitor outcome. When measuring TEE in field validation studies (doubly labelled water), high correlations with the TEE estimate of the activity monitor were found in most activity monitors. These correlations are,

however, to a large extent driven by patient characteristics (i.e. body weight, age, height) [87] which is an important predictor of TEE. Consequently, the comparison of TEE estimated from activity monitors, with TEE measured with indirect calorimetry or doubly labelled water is not necessarily a proof of validation. In a field setting it has been reported that only 19% of the TEE is accounted for by physical activity in both healthy subjects [87] and in patients with coronary heart disease [144].

Another factor that needs to be considered is the study population. Most of the study populations (88%) were healthy adults (from young healthy adults to healthy elderly). Only 12% of validation studies were performed in patients with chronic diseases (COPD, chronic heart failure, chronic organ failure, diabetes mellitus type II, obesity, peripheral arterial disease chronic low back pain



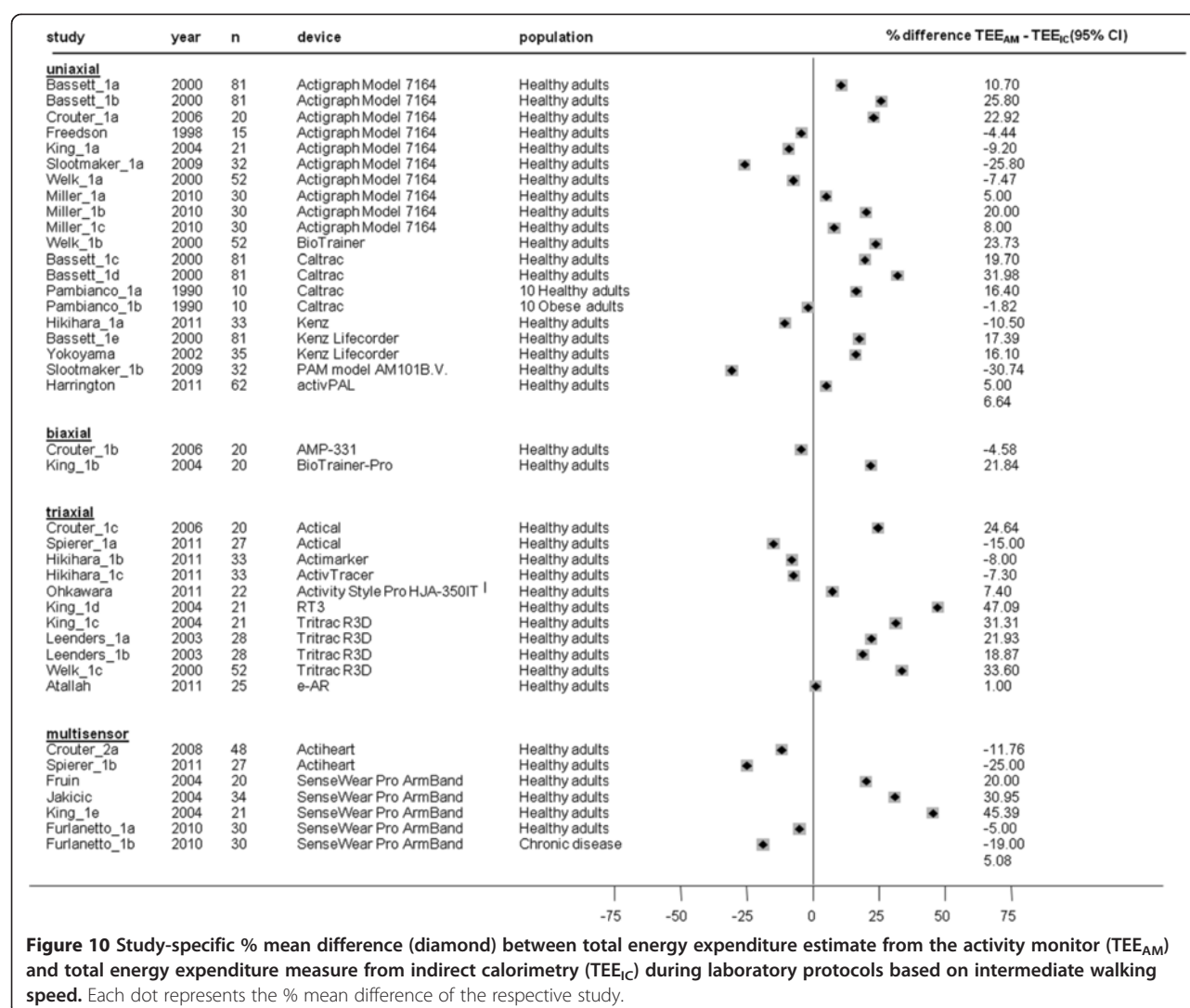


and fibromyalgia syndrome). These patients walk more slowly than healthy subjects, which is reflected, for example, by a reduced six minute walking distance [145,146]. This review, as well as original research [147], suggests that most monitors are less accurate at lower walking speeds. These findings are consistent with a systematic review of pedometers which found evidence of reduced accuracy during slow walking [148]. Hence, there is a need to perform validation studies specifically in chronic disease populations.

When measuring TEE in lab validation studies by assessment of oxygen consumption, higher correlations were reported for walking activities compared to other daily life activities which implies that the walking component of physical activity is better detected than other activities of daily living.

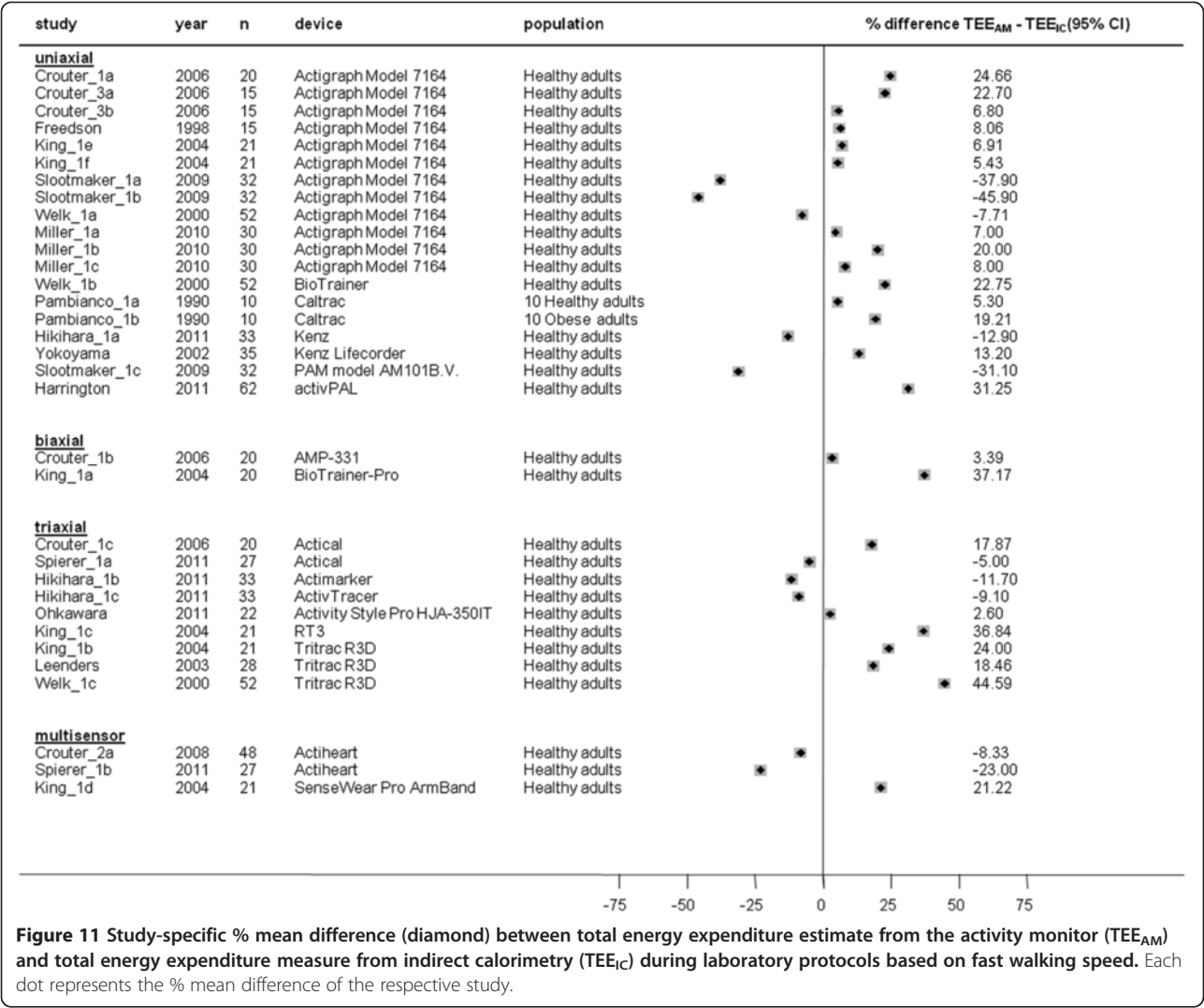
Most activity monitors use prediction equations to calculate energy expenditure from the activity signals. This

is helpful to validate monitors against indirect calorimetry, but, given the inherent inaccuracy of these estimates and fundamental differences between the different prediction equations (some of which are proprietary to particular device manufacturers), perhaps greater weight should be given to direct monitor outputs (steps, activity counts, VMU, etc.) and their relation to activity energy expenditure (AEE), rather than the ability of a monitor to estimate energy expenditure precisely [48,87-89]. It is very unlikely that an activity monitor will be able to capture accurately all the factors affecting energy expenditure (i.e. movement efficiency, resting metabolism, distribution of fat-free mass and fat mass). In patients with COPD, for example, Baarends et al. showed that non-resting energy expenditure (TEE-REE) was elevated in COPD compared to healthy controls [149]. Since it is generally accepted now that these patients are less active than healthy controls [150,151], it is clear that patients



expend more energy than controls to achieve the same movements. It would be unrealistic to expect an activity monitor to pick this up. Hence, the lack of accuracy against energy expenditure does not render activity monitors invalid tools to assess physical activity in patients over time (for which precision is more important) or to capture the physical activity level of a patient (for which validity, represented by the correlation with true energy expenditure is more important than absolute accuracy). The acceptable correlations between VO<sub>2</sub> and activity monitor outputs in triaxial and multisensor devices are therefore encouraging for the use of monitors to assess physical activity in an adult population. With specific validation studies, these findings can possibly be extrapolated to elderly and patients with chronic diseases.

The current systematic review may also help researchers to decide on appropriate activity monitor outcomes. Combination of the three most frequently available outcomes (TEE/AEE, steps and different levels of physical activity intensity), which is likely to provide a comprehensive insight in overall physical activity of a patient, is available in 3 uniaxial (Actigraph 7164/GT1M, Kenz Lifecorder EX and Polar Activity Watch 200), 1 biaxial (Biotrainer Pro), 3 triaxial (Dynaport Minimod, Actical and Actigraph GT3X) and 2 multisensor activity monitors (SenseWear Armband and multisensor board). Some general considerations can also be taken into account when selecting an activity monitor in clinical trials such as the type of monitoring (e.g. daily physical activity), size and scope of the study, usability of the monitor and cost [152].



Methodological issues

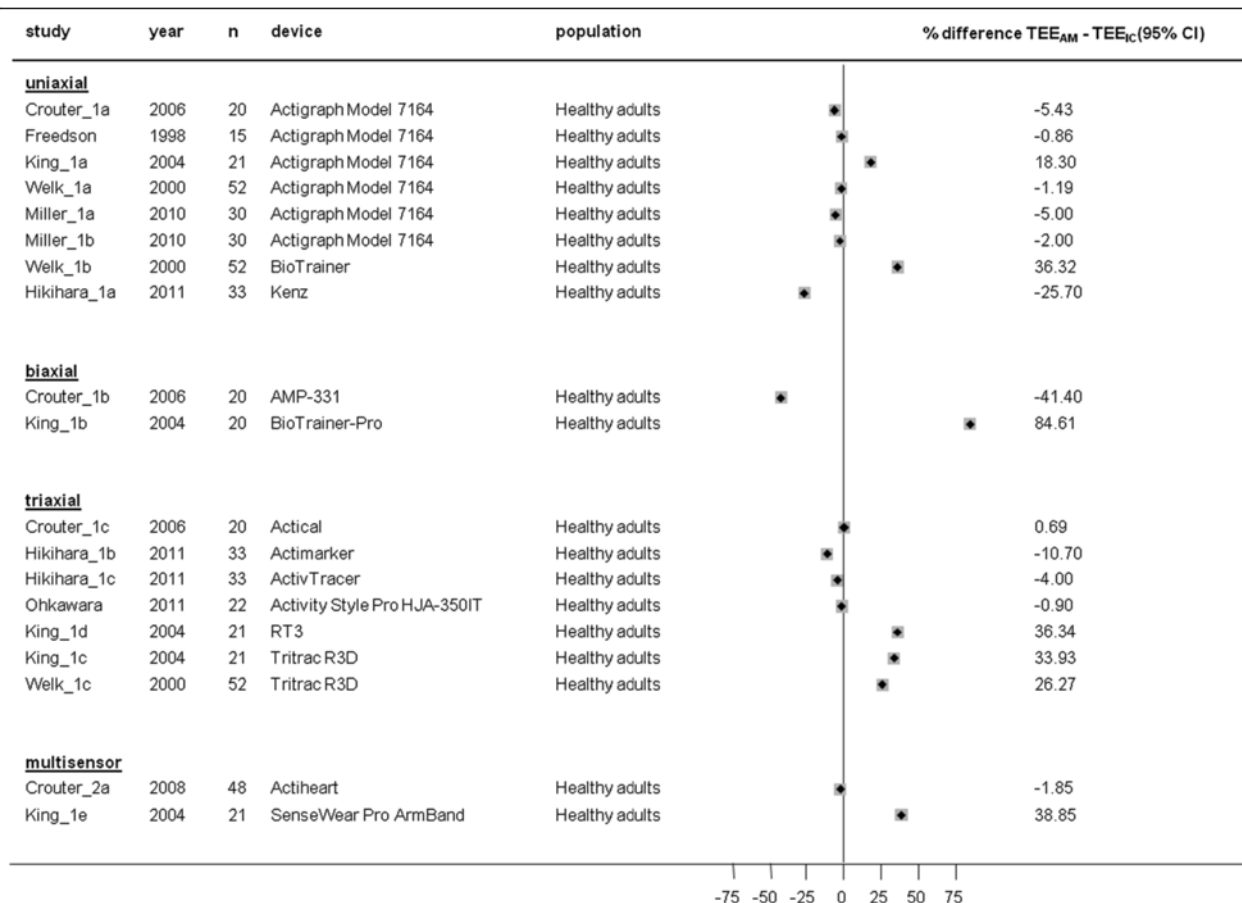
A point of difficulty in collecting, analysing and interpreting the data was the wide range of statistical approaches used in the original papers. Indeed, we had to compute the standard deviation of the mean difference (between EE<sub>AM</sub> and EE<sub>IC</sub>) because some field validation studies didn't report this.

Correlation analysis but also Bland and Altman analysis were the two main statistical approaches used in validation studies and were used for data extraction. A systematic review of the statistical methods used to validate physical activity questionnaires revealed similar findings, with the majority of the studies using correlation analysis compared to Bland and Altman analysis [153]. Correlation analyses are a common evaluation approach and allow statements on validity, whereas agreement between activity monitor and criterion method (indirect calorimetry) with Bland and Altman plots are

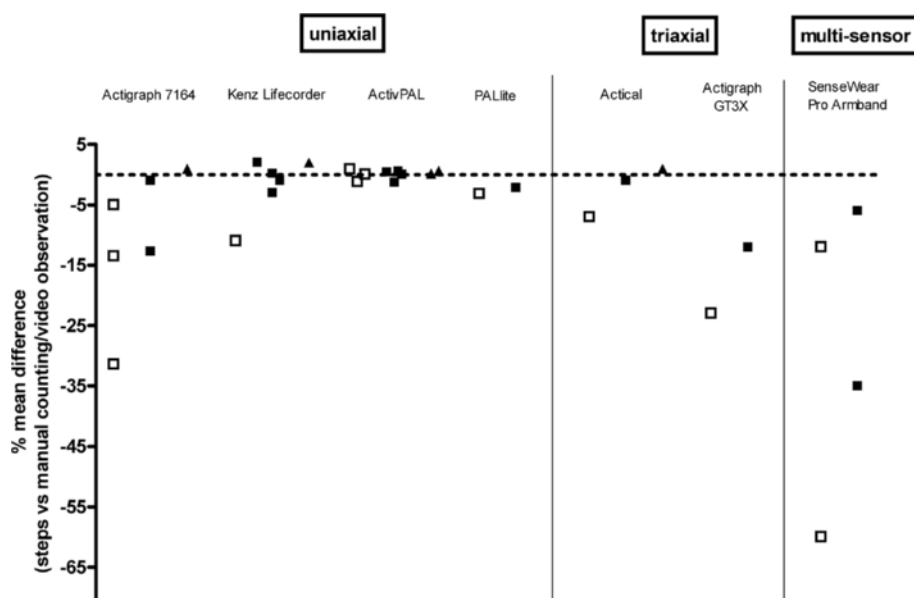
preferred when the aim is to identify systematic bias in measures [154]. Since not all activity monitors have the possibility to estimate total and/or active energy expenditure, this type of analysis is not uniformly applicable. Multiple regression analysis with TEE/AEE as the dependent variable is a correct technique to tackle this [87]. Consistent statistical guidelines for reporting the validity of an activity monitor would be helpful.

Conclusion

Validation studies of activity monitors are highly heterogeneous, and this is partly explained by the type of activity monitor and the activity monitor outcome. Since activity monitors are less accurate at slow walking speeds and information about validated activity monitors in chronic disease populations is lacking, proper validation studies in these populations are needed prior to their inclusion in clinical trials.



**Figure 12** Study-specific % mean difference (diamond) between total energy expenditure estimate from the activity monitor ( $TEE_{AM}$ ) and total energy expenditure measure from indirect calorimetry ( $TEE_{IC}$ ) during laboratory protocols based on running speed. Each dot represents the % mean difference of the respective study.



**Figure 13** Accuracy of steps at different walking speeds. The dots are reflecting walking speed: slow walking (<3.2 km/hr (□)), intermediate walking (3.2-6.4 km/hr (■)) and fast walking (6.5-8 km/hr (▲)).

## Additional files

### Additional file 1: Details of the search strategy terms in the different databases.

## Abbreviations

AEE: Active energy expenditure; AEE<sub>AM</sub>: Estimation of active energy expenditure by an activity monitor; AEE<sub>DLW</sub>: Measurement of active energy expenditure by doubly labelled water; AEE<sub>IC</sub>: Measurement of active energy expenditure by indirect calorimetry; AM: Activity monitor; COPD: Chronic obstructive pulmonary disease; DLW: Doubly labelled water; GPS: Global positioning system; IC: Indirect calorimetry; TEE: Total energy expenditure; TEE<sub>AM</sub>: Estimation of total energy expenditure by an activity monitor; TEE<sub>DLW</sub>: Measurement of total energy expenditure by doubly labelled water; TEE<sub>IC</sub>: Measurement of total energy expenditure by indirect calorimetry.

## Competing interests

The authors declare not having financial or non-financial competing interests.

## Authors' contributions

All authors contributed to the different processes in the systematic review (title and abstract screening, full text assessment and data extraction). HVR worked out an appropriate search term strategy in different databases. HVR and SG have been involved in analysing the data and drafting the manuscript which was revised by all the other authors. MP performed the statistical analysis. All authors read and approved the final manuscript.

## Authors' information

This systematic review is part of the PROactive project (www.proactivecopd.com) which aims to develop a Patient Reported Outcome (PRO) tool capturing physical activity in COPD in close harmony with a valid activity monitor.

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## References

- Warburton DE, Nicol CW, Bredin SS: **Health benefits of physical activity: the evidence.** *CMAJ* 2006, **174**:801–809.
- Blair SN, Cheng Y, Holder JS: **Is physical activity or physical fitness more important in defining health benefits?** *Med Sci Sports Exerc* 2001, **33**:S379–S399, discussion S419–S420.
- Garcia-Aymerich J, Lange P, Benet M, Schnohr P, Anto JM: **Regular physical activity reduces hospital admission and mortality in chronic obstructive pulmonary disease: a population based cohort study.** *Thorax* 2006, **61**:772–778.
- Caspersen CJ, Powell KE, Christenson GM: **Physical activity, exercise, and physical fitness: definitions and distinctions for health-related research.** *Public Health Rep* 1985, **100**:126–131.
- Steele BG, Belza B, Cain K, Warms C, Coppersmith J, Howard J: **Bodies in motion: monitoring daily activity and exercise with motion sensors in people with chronic pulmonary disease.** *J Rehabil Res Dev* 2003, **40**:45–58.
- Garcia-Aymerich J, Serra I, Gomez FP, Farrero E, Balcells E, Rodriguez DA, de Batlle J, Gimeno E, Donaire-Gonzalez D, Orozco-Levi M, et al: **Physical activity and clinical and functional status in COPD.** *Chest* 2009, **136**:62–70.
- Bassett DR Jr, Ainsworth BE, Swartz AM, Strath SJ, O'Brien WL, King GA: **Validity of four motion sensors in measuring moderate intensity physical activity.** *Med Sci Sports Exerc* 2000, **32**:S471–S480.
- Le Masurier GC, Tudor-Locke C: **Comparison of pedometer and accelerometer accuracy under controlled conditions.** *Med Sci Sports Exerc* 2003, **35**:867–871.
- Plasqui G, Westerterp KR: **Physical activity assessment with accelerometers: an evaluation against doubly labeled water.** *Obesity (Silver Spring)* 2007, **15**:2371–2379.
- Cyarto EV, Myers AM, Tudor-Locke C: **Pedometer accuracy in nursing home and community-dwelling older adults.** *Med Sci Sports Exerc* 2004, **36**:205–209.
- Giacomozzi C, Caselli A, Macellari V, Giurato L, Lardieri L, Uccioli L: **Walking strategy in diabetic patients with peripheral neuropathy.** *Diabetes Care* 2002, **25**:1451–1457.
- Guazzi M, Dickstein K, Vicenzi M, Arena R: **Six-minute walk test and cardiopulmonary exercise testing in patients with chronic heart failure: a comparative analysis on clinical and prognostic insights.** *Circ Heart Fail* 2009, **2**:549–555.
- Corey DM, Dunlap WP: **Averaging Correlations: expected Values and Bias in Combined Pearson rs and Fisher's z Transformations.** *J Gen Psychol* 1998, **125**:245–261.
- Leenders NY, Sherman WM, Nagaraja HN: **Energy expenditure estimated by accelerometry and doubly labeled water: do they agree?** *Med Sci Sports Exerc* 2006, **38**:2165–2172.
- Adams SA, Matthews CE, Ebbeling CB, Moore CG, Cunningham JE, Fulton J, Hebert JR: **The effect of social desirability and social approval on self-reports of physical activity.** *Am J Epidemiol* 2005, **161**:389–398.
- Leenders NY, Sherman WM, Nagaraja HN, Kien CL: **Evaluation of methods to assess physical activity in free-living conditions.** *Med Sci Sports Exerc* 2001, **33**:1233–1240.
- Dalton AF, Ni Scanail C, Carew S, Lyons D, OL G: **A clinical evaluation of a remote mobility monitoring system based on SMS messaging.** *Conf Proc IEEE Eng Med Biol Soc* 2007, **2007**:2327–2330.



18. Kochersberger G, McConnell E, Kuchibhatla MN, Pieper C: **The reliability, validity, and stability of a measure of physical activity in the elderly.** *Arch Phys Med Rehabil* 1996, **77**:793-795.
19. Masse LC, Fulton JE, Watson KL, Heesch KC, Kohl HW 3rd, Blair SN, Tortolero SR: **Detecting bouts of physical activity in a field setting.** *Res Q Exerc Sport* 1999, **70**:212-219.
20. McClain JJ, Craig CL, Sisson SB, Tudor-Locke C: **Comparison of Lifecorder EX and ActiGraph accelerometers under free-living conditions.** *Appl Physiol Nutr Metab* 2007, **32**:753-761.
21. Paul DR, Kramer M, Moshfegh AJ, Baer DJ, Rumpler WV: **Comparison of two different physical activity monitors.** *BMC Med Res Methodol* 2007, **7**:26.
22. Lof M, Hannestad U, Forsum E: **Comparison of commonly used procedures, including the doubly-labelled water technique, in the estimation of total energy expenditure of women with special reference to the significance of body fatness.** *Br J Nutr* 2003, **90**:961-968.
23. Masse LC, Fulton JE, Watson KL, Mahar MT, Meyers MC, Wong WW: **Influence of body composition on physical activity validation studies using doubly labeled water.** *J Appl Physiol* 2004, **96**:1357-1364.
24. Patrik Johansson H, Rossander-Hulthen L, Slinde F, Ekblom B: **Accelerometry combined with heart rate telemetry in the assessment of total energy expenditure.** *Br J Nutr* 2006, **95**:631-639.
25. Brooks AG, Gunn SM, Withers RT, Gore CJ, Plummer JL: **Predicting walking METs and energy expenditure from speed or accelerometry.** *Med Sci Sports Exerc* 2005, **37**:1216-1223.
26. Crouter SE, Churilla JR, Bassett DR Jr: **Estimating energy expenditure using accelerometers.** *Eur J Appl Physiol* 2006, **98**:601-612.
27. Focht BC: **Initial Validation of the CSA Activity Monitor During Rehabilitative Exercise Among Older Adults With Chronic Disease.** *Journal of Aging and Physical Activity* 2003, **11**:293-304.
28. Freedson PS, Melanson E, Sirard J: **Calibration of the Computer Science and Applications, Inc. accelerometer.** *Med Sci Sports Exerc* 1998, **30**:777-781.
29. Fudge BW, Wilson J, Easton C, Irwin L, Clark J, Haddow O, Kayser B, Pitsiladis YP: **Estimation of oxygen uptake during fast running using accelerometry and heart rate.** *Med Sci Sports Exerc* 2007, **39**:192-198.
30. Heil DP: **Body size as a determinant of activity monitor output during overground walking.** *JEP online* 2003, **6**:1-11.
31. Hendelman D, Miller K, Baggett C, Debold E, Freedson P: **Validity of accelerometry for the assessment of moderate intensity physical activity in the field.** *Med Sci Sports Exerc* 2000, **32**:S442-S449.
32. King GA, Torres N, Potter C, Brooks TJ, Coleman KJ: **Comparison of activity monitors to estimate energy cost of treadmill exercise.** *Med Sci Sports Exerc* 2004, **36**:1244-1251.
33. Leenders NY, Nelson TE, Sherman WM: **Ability of different physical activity monitors to detect movement during treadmill walking.** *Int J Sports Med* 2003, **24**:43-50.
34. Melanson EL Jr, Freedson PS: **Validity of the Computer Science and Applications, Inc. (CSA) activity monitor.** *Med Sci Sports Exerc* 1995, **27**:934-940.
35. Nichols JF, Patterson P, Early T: **A validation of a physical activity monitor for young and older adults.** *Can J Sport Sci* 1992, **17**:299-303.
36. Patterson SM, Krantz DS, Montgomery LC, Deuster PA, Hedges SM, Nebel LE: **Automated physical activity monitoring: validation and comparison with physiological and self-report measures.** *Psychophysiology* 1993, **30**:296-305.
37. Slootmaker SM, Chin APMJ, Schuit AJ, van Mechelen W, Koppes LL: **Concurrent validity of the PAM accelerometer relative to the MTI Actigraph using oxygen consumption as a reference.** *Scand J Med Sci Sports* 2009, **19**:36-43.
38. Stone MR, Eslinger DW, Tremblay MS: **Comparative validity assessment of five activity monitors: does being a child matter?** *Pediatr Exerc Sci* 2007, **19**:291-309.
39. Strath SJ, Bassett DR Jr, Thompson DL, Swartz AM: **Validity of the simultaneous heart rate-motion sensor technique for measuring energy expenditure.** *Med Sci Sports Exerc* 2002, **34**:888-894.
40. Swartz AM, Strath SJ, Bassett DR Jr, O'Brien WL, King GA, Ainsworth BE: **Estimation of energy expenditure using CSA accelerometers at hip and wrist sites.** *Med Sci Sports Exerc* 2000, **32**:S450-S456.
41. Welk GJ, Blair SN, Wood K, Jones S, Thompson RW: **A comparative evaluation of three accelerometry-based physical activity monitors.** *Med Sci Sports Exerc* 2000, **32**:S489-S497.
42. Crouter SE, Clowers KG, Bassett DR Jr: **A novel method for using accelerometer data to predict energy expenditure.** *J Appl Physiol* 2006, **100**:1324-1331.
43. Nichols JF, Morgan CG, Chabot LE, Sallis JF, Calfas KJ: **Assessment of physical activity with the Computer Science and Applications, Inc., accelerometer: laboratory versus field validation.** *Res Q Exerc Sport* 2000, **71**:36-43.
44. Eslinger DW, Probert A, Gorber SC, Bryan S, Laviolette M, Tremblay MS: **Validity of the Actical accelerometer step-count function.** *Med Sci Sports Exerc* 2007, **39**:1200-1204.
45. Storti KL, Pettee KK, Brach JS, Talkowski JB, Richardson CR, Kriska AM: **Gait speed and step-count monitor accuracy in community-dwelling older adults.** *Med Sci Sports Exerc* 2008, **40**:59-64.
46. Berntsen S, Hageberg R, Aandstad A, Mowinckel P, Anderssen SA, Carlsen KH, Andersen LB: **Validity of physical activity monitors in adults participating in free-living activities.** *Br J Sports Med* 2010, **44**:657-664.
47. Miller NE, Strath SJ, Swartz AM, Cashin SE: **Estimating absolute and relative physical activity intensity across age via accelerometry in adults.** *J Aging Phys Act* 2010, **18**:158-170.
48. Assah FK, Ekelund U, Brage S, Corder K, Wright A, Mbanya JC, Wareham NJ: **Predicting physical activity energy expenditure using accelerometry in adults from sub-Saharan Africa.** *Obesity (Silver Spring)* 2009, **17**:1588-1595.
49. Rothney MP, Brychta RJ, Meade NN, Chen KY, Buchowski MS: **Validation of the ActiGraph two-regression model for predicting energy expenditure.** *Med Sci Sports Exerc* 2010, **42**:1785-1792.
50. Colbert LH, Matthews CE, Havighurst TC, Kim K, Schoeller DA: **Comparative validity of physical activity measures in older adults.** *Med Sci Sports Exerc* 2011, **43**:867-876.
51. Abel MG, Hannon JC, Sell K, Lillie T, Conlin G, Anderson D: **Validation of the Kenz Lifecorder EX and ActiGraph GT1M accelerometers for walking and running in adults.** *Appl Physiol Nutr Metab* 2008, **33**:1155-1164.
52. Edwards AG, Hill JO, Byrnes WC, Browning RC: **Accuracy of optimized branched algorithms to assess activity-specific physical activity energy expenditure.** *Med Sci Sports Exerc* 2010, **42**:672-682.
53. Kozey SL, Lyden K, Howe CA, Staudenmayer JW, Freedson PS: **Accelerometer output and MET values of common physical activities.** *Med Sci Sports Exerc* 2010, **42**:1776-1784.
54. Lyden K, Kozey SL, Staudenmayer JW, Freedson PS: **A comprehensive evaluation of commonly used accelerometer energy expenditure and MET prediction equations.** *Eur J Appl Physiol* 2011, **111**:187-201.
55. Eslinger DW, Rowlands AV, Hurst TL, Catt M, Murray P, Eston RG: **Validation of the GENE Accelerometer.** *Med Sci Sports Exerc* 2010, **43**:1085-1093.
56. Kuffel EE, Crouter SE, Haas JD, Frongillo EA, Bassett DR Jr: **Validity of estimating minute-by-minute energy expenditure of continuous walking bouts by accelerometry.** *Int J Behav Nutr Phys Act* 2011, **8**:92.
57. Harrington DM, Welk GJ, Donnelly AE: **Validation of MET estimates and step measurement using the ActivPAL physical activity logger.** *J Sports Sci* 2011, **29**:627-633.
58. Fogelholm M, Hiilloskorpi H, Laukkanen R, Oja P, Van Marken Lichtenbelt W, Westerterp K: **Assessment of energy expenditure in overweight women.** *Med Sci Sports Exerc* 1998, **30**:1191-1197.
59. Fuller Z, Horgan G, O'Reilly LM, Ritz P, Milne E, Stubbs RJ: **Comparing different measures of energy expenditure in human subjects resident in a metabolic facility.** *Eur J Clin Nutr* 2008, **62**:560-569.
60. Gardner AW, Womack CJ, Sieminski DJ, Montgomery PS, Killewich LA, Fonong T: **Relationship between free-living daily physical activity and ambulatory measures in older claudicants.** *Angiology* 1998, **49**:327-337.
61. Starling RD, Matthews DE, Ades PA, Poehlman ET: **Assessment of physical activity in older individuals: a doubly labeled water study.** *J Appl Physiol* 1999, **86**:2090-2096.
62. Choquette S, Chuin A, Lalancette DA, Brochu M, Dionne IJ: **Predicting energy expenditure in elders with the metabolic cost of activities.** *Med Sci Sports Exerc* 2009, **41**:1915-1920.

63. Fehling PC, Smith DL, Warner SE, Dalsky GP: **Comparison of accelerometers with oxygen consumption in older adults during exercise.** *Med Sci Sports Exerc* 1999, **31**:171–175.
64. Hageman PA: **Comparison of two Physical Activity Monitors During a 1-Mile Walking field test.** *JEP online* 2004, **7**:102–110.
65. Pambianco G, Wing RR, Robertson R: **Accuracy and reliability of the Caltrac accelerometer for estimating energy expenditure.** *Med Sci Sports Exerc* 1990, **22**:858–862.
66. Rafamantanantsoa HH, Ebine N, Yoshioka M, Higuchi H, Yoshitake Y, Tanaka H, Saitoh S, Jones PJ: **Validation of three alternative methods to measure total energy expenditure against the doubly labeled water method for older Japanese men.** *J Nutr Sci Vitaminol (Tokyo)* 2002, **48**:517–523.
67. Yamada Y, Yokoyama K, Noriyasu R, Osaki T, Adachi T, Itoi A, Naito Y, Morimoto T, Kimura M, Oda S: **Light-intensity activities are important for estimating physical activity energy expenditure using uniaxial and triaxial accelerometers.** *Eur J Appl Physiol* 2009, **105**:141–152.
68. Kumahara H, Schutz Y, Ayabe M, Yoshioka M, Yoshitake Y, Shindo M, Ishii K, Tanaka H: **The use of uniaxial accelerometry for the assessment of physical-activity-related energy expenditure: a validation study against whole-body indirect calorimetry.** *Br J Nutr* 2004, **91**:235–243.
69. Schneider PL, Crouter SE, Lukajic O, Bassett DR Jr: **Accuracy and reliability of 10 pedometers for measuring steps over a 400-m walk.** *Med Sci Sports Exerc* 2003, **35**:1779–1784.
70. Ohkawara K, Ishikawa-Takata K, Park JH, Tabata I, Tanaka S: **How much locomotive activity is needed for an active physical activity level: analysis of total step counts.** *BMC Res Notes* 2011, **4**:512.
71. Yokoyama Y, Kawamura T, Tamakoshi A, Noda A, Hirai M, Saito H, Ohno Y: **Comparison of accelerometry and oxymetry for measuring daily physical activity.** *Circ J* 2002, **66**:751–754.
72. Grant PM, Dall PM, Mitchell SL, Granat MH: **Activity-monitor accuracy in measuring step number and cadence in community-dwelling older adults.** *J Aging Phys Act* 2008, **16**:201–214.
73. Ryan CG, Grant PM, Tigbe WW, Granat MH: **The validity and reliability of a novel activity monitor as a measure of walking.** *Br J Sports Med* 2006, **40**:779–784.
74. Maddocks M, Petrou A, Skipper L, Wilcock A: **Validity of three accelerometers during treadmill walking and motor vehicle travel.** *Br J Sports Med* 2010, **44**:606–608.
75. Chen KY, Acra SA, Majchrzak K, Donahue CL, Baker L, Clemens L, Sun M, Buchowski MS: **Predicting energy expenditure of physical activity using hip- and wrist-worn accelerometers.** *Diabetes Technol Ther* 2003, **5**:1023–1033.
76. Welk GJ, Almeida J, Morss G: **Laboratory calibration and validation of the Biotrainer and Actitrac activity monitors.** *Med Sci Sports Exerc* 2003, **35**:1057–1064.
77. Kane NA, Simmons MC, John D, Thompson DL, Bassett DR: **Validity of the Nike+ device during walking and running.** *Int J Sports Med* 2010, **31**:101–105.
78. Brugniaux JV, Niva A, Pulkkinen I, Laukkanen RM, Richalet JP, Pichon AP: **Polar Activity Watch 200: a new device to accurately assess energy expenditure.** *Br J Sports Med* 2010, **44**:245–249.
79. Connolly CP, Coe DP, Kendrick JM, Bassett DR Jr, Thompson DL: **Accuracy of physical activity monitors in pregnant women.** *Med Sci Sports Exerc* 2010, **43**:1100–1105.
80. Jacobi D, Perrin AE, Grosman N, Dore MF, Normand S, Oppert JM, Simon C: **Physical activity-related energy expenditure with the RT3 and TriTrac accelerometers in overweight adults.** *Obesity (Silver Spring)* 2007, **15**:950–956.
81. Maddison R, Jiang Y, Hoorn SV, Mhurchu CN, Lawes CM, Rodgers A, Rush E: **Estimating energy expenditure with the RT3 triaxial accelerometer.** *Res Q Exerc Sport* 2009, **80**:249–256.
82. DeVoe D, Gotshall R, McArthur T: **Comparison of the RT3 Research Tracker and Tritrac R3D accelerometers.** *Percept Mot Skills* 2003, **97**:510–518.
83. Howe CA, Staudenmayer JW, Freedson PS: **Accelerometer prediction of energy expenditure: vector magnitude versus vertical axis.** *Med Sci Sports Exerc* 2009, **41**:2199–2206.
84. Campbell KL, Crocker PR, McKenzie DC: **Field evaluation of energy expenditure in women using Tritrac accelerometers.** *Med Sci Sports Exerc* 2002, **34**:1667–1674.
85. Chen KY, Sun M: **Improving energy expenditure estimation by using a triaxial accelerometer.** *J Appl Physiol* 1997, **83**:2112–2122.
86. Jakicic JM, Winters C, Lagally K, Ho J, Robertson RJ, Wing RR: **The accuracy of the TriTrac-R3D accelerometer to estimate energy expenditure.** *Med Sci Sports Exerc* 1999, **31**:747–754.
87. Plasqui G, Joosen AM, Kester AH, Goris AH, Westerterp KR: **Measuring free-living energy expenditure and physical activity with triaxial accelerometry.** *Obes Res* 2005, **13**:1363–1369.
88. Bouten CV, Verboeket-van de Venne WP, Westerterp KR, Verduin M, Janssen JD: **Daily physical activity assessment: comparison between movement registration and doubly labeled water.** *J Appl Physiol* 1996, **81**:1019–1026.
89. Meijer EP, Goris AH, Wouters L, Westerterp KR: **Physical inactivity as a determinant of the physical activity level in the elderly.** *Int J Obes Relat Metab Disord* 2001, **25**:935–939.
90. Bonomi AG, Plasqui G, Goris AH, Westerterp KR: **Estimation of free-living energy expenditure using a novel activity monitor designed to minimize obtrusiveness.** *Obesity (Silver Spring)* 2010, **18**:1845–1851.
91. Goris AH, Meijer EP, Kester A, Westerterp KR: **Use of a triaxial accelerometer to validate reported food intakes.** *Am J Clin Nutr* 2001, **73**:549–553.
92. Meijer GA, Westerterp KR, van Hulsel AM, ten Hoor F: **Physical activity and energy expenditure in lean and obese adult human subjects.** *Eur J Appl Physiol Occup Physiol* 1992, **65**:525–528.
93. Pietilainen KH, Kaprio J, Borg P, Plasqui G, Yki-Jarvinen H, Kujala UM, Rose RJ, Westerterp KR, Rissanen A: **Physical inactivity and obesity: a vicious circle.** *Obesity (Silver Spring)* 2008, **16**:409–414.
94. Verbunt JA, Westerterp KR, van der Heijden GJ, Seelen HA, Vlaeyen JW, Knottnerus JA: **Physical activity in daily life in patients with chronic low back pain.** *Arch Phys Med Rehabil* 2001, **82**:726–730.
95. Bouten CV, Koekkoek KT, Verduin M, Kodde R, Janssen JD: **A triaxial accelerometer and portable data processing unit for the assessment of daily physical activity.** *IEEE Trans Biomed Eng* 1997, **44**:136–147.
96. Bouten CV, Westerterp KR, Verduin M, Janssen JD: **Assessment of energy expenditure for physical activity using a triaxial accelerometer.** *Med Sci Sports Exerc* 1994, **26**:1516–1523.
97. Levine JA, Baukol PA, Westerterp KR: **Validation of the Tracmor triaxial accelerometer system for walking.** *Med Sci Sports Exerc* 2001, **33**:1593–1597.
98. Bonomi AG, Plasqui G, Goris AH, Westerterp KR: **Estimation of free-living energy expenditure using a novel activity monitor designed to minimize obtrusiveness.** *Obesity (Silver Spring)* 2010, **18**:1845–1851.
99. Brandes M, Rosenbaum D: **Correlations between the step activity monitor and the DynaPort ADL-monitor.** *Clin Biomech (Bristol, Avon)* 2004, **19**:91–94.
100. Langer D, Gosselink R, Sena R, Burtin C, Decramer M, Troosters T: **Validation of two activity monitors in patients with COPD.** *Thorax* 2009, **64**:641–642.
101. van Hees VT, van Lummel RC, Westerterp KR: **Estimating activity-related energy expenditure under sedentary conditions using a tri-axial seismic accelerometer.** *Obesity (Silver Spring)* 2009, **17**:1287–1292.
102. Carter J, Wilkinson D, Blacker S, Rayson M, Bilzon J, Izard R, Coward A, Wright A, Nevill A, Rennie K, et al: **An investigation of a novel three-dimensional activity monitor to predict free-living energy expenditure.** *J Sports Sci* 2008, **26**:553–561.
103. Horner FE, Rayson MP, Bilzon JL: **Reliability and validity of the 3DNX accelerometer during mechanical and human treadmill exercise testing.** *Int J Obes (Lond)* 2011, **35**(Suppl 1):S88–S97.
104. Hikiyama Y, Tanaka S, Ohkawara K, Ishikawa-Takata K, Tabata I: **Validation and Comparison of Three Accelerometers for Measuring Physical Activity Intensity During Nonlocomotive Activities and Locomotive Movements.** *J Phys Act Health* 2011.
105. Dugas LR, Carstens MA, Ebersole K, Schoeller DA, Durazo-Arvizu RA, Lambert EV, Luke A: **Energy expenditure in young adult urban informal settlement dwellers in South Africa.** *Eur J Clin Nutr* 2009, **63**:805–807.
106. Heil DP: **Predicting activity energy expenditure using the Actical activity monitor.** *Res Q Exerc Sport* 2006, **77**:64–80.
107. Crouter SE, Schneider PL, Karabulut M, Bassett DR Jr: **Validity of 10 electronic pedometers for measuring steps, distance, and energy cost.** *Med Sci Sports Exerc* 2003, **35**:1455–1460.



108. Spierer DK, Hagins M, Rundle A, Pappas E: **A comparison of energy expenditure estimates from the Actiheart and Actical physical activity monitors during low intensity activities, walking, and jogging.** *Eur J Appl Physiol* 2011, **111**:659–667.
109. Crouter SE, Dellavalle DM, Horton M, Haas JD, Frongillo EA, Bassett DR Jr: **Validity of the Actical for estimating free-living physical activity.** *Eur J Appl Physiol* 2011, **111**:1381–1389.
110. Heiermann S, Khalaj Hedayati K, Muller MJ, Dittmar M: **Accuracy of a portable multisensor body monitor for predicting resting energy expenditure in older people: a comparison with indirect calorimetry.** *Gerontology* 2010, **57**:473–479.
111. Duncan GE, Lester J, Migotsky S, Goh J, Higgins L, Borriello G: **Accuracy of a novel multi-sensor board for measuring physical activity and energy expenditure.** *Eur J Appl Physiol* 2011, **111**:2025–2032.
112. Hooker SP, Feeney A, Hutto B, Pfeiffer KA, McIver K, Heil DP, Vena JE, Lamonte MJ, Blair SN: **Validation of the actical activity monitor in middle-aged and older adults.** *J Phys Act Health* 2011, **8**:372–381.
113. Atallah L, Leong JJ, Lo B, Yang GZ: **Energy expenditure prediction using a miniaturized ear-worn sensor.** *Med Sci Sports Exerc* 2011, **43**:1369–1377.
114. Manohar C, McCrady S, Pavlidis IT, Levine JA: **An accelerometer-based earpiece to monitor and quantify physical activity.** *J Phys Act Health* 2009, **6**:781–789.
115. van Hees VT, Renstrom F, Wright A, Gradmark A, Catt M, Chen KY, Lof M, Bluck L, Pomeroy J, Wareham NJ, et al: **Estimation of daily energy expenditure in pregnant and non-pregnant women using a wrist-worn tri-axial accelerometer.** *PLoS One* 2011, **6**:e22922.
116. Ohkawara K, Oshima Y, Hikiyama Y, Ishikawa-Takata K, Tabata I, Tanaka S: **Real-time estimation of daily physical activity intensity by a triaxial accelerometer and a gravity-removal classification algorithm.** *Br J Nutr* 2011, **105**:1681–1691.
117. Annegarn J, Spruit MA, Uszko-Lencer NH, Vanbelle S, Savelberg HH, Schols AM, Wouters EF, Meijer K: **Objective physical activity assessment in patients with chronic organ failure: a validation study of a new single-unit activity monitor.** *Arch Phys Med Rehabil* 2011, **92**:1852–1857. e1851.
118. Harris AM, McAlpine DE, Shirbhate R, Manohar CU, Levine JA: **Measurement of daily activity in restrictive type anorexia nervosa.** *Int J Eat Disord* 2008, **41**:280–283.
119. Arvidsson D, Slinde F, Nordenson A, Larsson S, Hulthen L: **Validity of the ActiReg system in assessing energy requirement in chronic obstructive pulmonary disease patients.** *Clin Nutr* 2006, **25**:68–74.
120. Hustvedt BE, Christophersen A, Johnsen LR, Tomten H, McNeill G, Haggarty P, Lovo A: **Description and validation of the ActiReg: a novel instrument to measure physical activity and energy expenditure.** *Br J Nutr* 2004, **92**:1001–1008.
121. Bussmann JB, Hartgerink I, van der Woude LH, Stam HJ: **Measuring physical strain during ambulation with accelerometry.** *Med Sci Sports Exerc* 2000, **32**:1462–1471.
122. Mignault D, St-Onge M, Karelis AD, Allison DB, Rabasa-Lhoret R: **Evaluation of the Portable HealthWear Armband: a device to measure total daily energy expenditure in free-living type 2 diabetic individuals.** *Diabetes Care* 2005, **28**:225–227.
123. St-Onge M, Mignault D, Allison DB, Rabasa-Lhoret R: **Evaluation of a portable device to measure daily energy expenditure in free-living adults.** *Am J Clin Nutr* 2007, **85**:742–749.
124. Johannsen DL, Calabro MA, Stewart J, Franke W, Rood JC, Welk GJ: **Accuracy of armband monitors for measuring daily energy expenditure in healthy adults.** *Med Sci Sports Exerc* 2010, **42**:2134–2140.
125. Koehler K, Braun H, de Marees M, Fusch G, Fusch C, Schaenzer W: **Assessing energy expenditure in male endurance athletes: validity of the SenseWear Armband.** *Med Sci Sports Exerc* 2011, **43**:1328–1333.
126. Mackey DC, Manini TM, Schoeller DA, Koster A, Glynn NW, Goodpaster BH, Satterfield S, Newman AB, Harris TB, Cummings SR: **Validation of an armband to measure daily energy expenditure in older adults.** *J Gerontol A Biol Sci Med Sci* 2011, **66**:1108–1113.
127. Cole PJ, LeMura LM, Klinger TA, Strohecker K, McConnell TR: **Measuring energy expenditure in cardiac patients using the Body Media Armband versus indirect calorimetry. A validation study.** *J Sports Med Phys Fitness* 2004, **44**:262–271.
128. Fruin ML, Rankin JW: **Validity of a multi-sensor armband in estimating rest and exercise energy expenditure.** *Med Sci Sports Exerc* 2004, **36**:1063–1069.
129. Jakicic JM, Marcus M, Gallagher KI, Randall C, Thomas E, Goss FL, Robertson RJ: **Evaluation of the SenseWear Pro Armband to assess energy expenditure during exercise.** *Med Sci Sports Exerc* 2004, **36**:897–904.
130. Patel SA, Benzo RP, Slivka WA, Sciurba FC: **Activity monitoring and energy expenditure in COPD patients: a validation study.** *COPD* 2007, **4**:107–112.
131. Dwyer TJ, Alison JA, McKeough ZJ, Elkins MR, Bye PT: **Evaluation of the SenseWear activity monitor during exercise in cystic fibrosis and in health.** *Respir Med* 2009, **103**:1511–1517.
132. Furlanetto KC, Bisca GW, Oldenberg N, Sant'anna TJ, Morakami FK, Camillo CA, Cavalheri V, Hernandez NA, Probst VS, Ramos EM, et al: **Step counting and energy expenditure estimation in patients with chronic obstructive pulmonary disease and healthy elderly: accuracy of 2 motion sensors.** *Arch Phys Med Rehabil* 2010, **91**:261–267.
133. Hill K, Dolmage TE, Woon L, Goldstein R, Brooks D: **Measurement properties of the SenseWear armband in adults with chronic obstructive pulmonary disease.** *Thorax* 2010, **65**:486–491.
134. Drenowatz C, Eisenmann JC: **Validation of the SenseWear Armband at high intensity exercise.** *Eur J Appl Physiol* 2011, **111**:883–887.
135. Cavalheri V, Donaria L, Ferreira T, Finatti M, Camillo CA, Cipulo Ramos EM, Pitta F: **Energy expenditure during daily activities as measured by two motion sensors in patients with COPD.** *Respir Med* 2011, **105**:922–929.
136. Berntsen S, Stafne SN, Morkved S: **Physical activity monitor for recording energy expenditure in pregnancy.** *Acta Obstet Gynecol Scand* 2010, **90**:903–907.
137. Brazeau AS, Karelis AD, Mignault D, Lacroix MJ, Prud'homme D, Rabasa-Lhoret R: **Accuracy of the SenseWear Armband during ergocycling.** *Int J Sports Med* 2011, **32**:761–764.
138. Munguia-Izquierdo D, Santalla A, Legaz-Arrese A: **Evaluation of a wearable body monitoring device during treadmill walking and jogging in patients with fibromyalgia syndrome.** *Arch Phys Med Rehabil* 2012, **93**:115–122.
139. Crouter SE, Churilla JR, Bassett DR Jr: **Accuracy of the Actiheart for the assessment of energy expenditure in adults.** *Eur J Clin Nutr* 2008, **62**:704–711.
140. Lof M: **Physical activity pattern and activity energy expenditure in healthy pregnant and non-pregnant Swedish women.** *Eur J Clin Nutr* 2011, **65**:1295–1301.
141. Kwon S, Jamal M, Zamba GK, Stumbo P, Samuel I: **Validation of a novel physical activity assessment device in morbidly obese females.** *J Obes* 2010, **2010**:1–8.
142. Borrell B: **Epidemiology: every bite you take.** *Nature* 2011, **470**:320–322.
143. Schenk AK, Witbrodt BC, Hoarty CA, Carlson RH Jr, Goulding EH, Potter JF, Bonasera SJ: **Cellular telephones measure activity and lifespan in community-dwelling adults: proof of principle.** *J Am Geriatr Soc* 2011, **59**:345–352.
144. Ades PA, Savage PD, Brochu M, Tischler MD, Lee NM, Poehlman ET: **Resistance training increases total daily energy expenditure in disabled older women with coronary heart disease.** *J Appl Physiol* 2005, **98**:1280–1285.
145. Gosselink R, Troosters T, Decramer M: **Peripheral muscle weakness contributes to exercise limitation in COPD.** *Am J Respir Crit Care Med* 1996, **153**:976–980.
146. Balashov K, Feldman DE, Savard S, Houde S, Frenette M, Ducharme A, Giannetti N, Michel C, Pilote L: **Percent predicted value for the 6-minute walk test: using norm-referenced equations to characterize severity in persons with CHF.** *J Card Fail* 2008, **14**:75–81.
147. Pitta F, Troosters T, Probst VS, Spruit MA, Decramer M, Gosselink R: **Quantifying physical activity in daily life with questionnaires and motion sensors in COPD.** *Eur Respir J* 2006, **27**:1040–1055.
148. Tudor-Locke C, Williams JE, Reis JP, Pluto D: **Utility of pedometers for assessing physical activity: convergent validity.** *Sports Med* 2002, **32**:795–808.
149. Baarends EM, Schols AM, Pannemans DL, Westerterp KR, Wouters EF: **Total free living energy expenditure in patients with severe chronic**

obstructive pulmonary disease. *Am J Respir Crit Care Med* 1997, **155**:549–554.

150. Vorrink SN, Kort HS, Troosters T, Lammers JW: **Level of daily physical activity in individuals with COPD compared with healthy controls.** *Respir Res* 2011, **12**:33.
151. Watz H, Waschki B, Meyer T, Magnussen H: **Physical activity in patients with COPD.** *Eur Respir J* 2009, **33**:262–272.
152. Murphy SL: **Review of physical activity measurement using accelerometers in older adults: considerations for research design and conduct.** *Prev Med* 2009, **48**:108–114.
153. Schmidt ME, Steindorf K: **Statistical methods for the validation of questionnaires—discrepancy between theory and practice.** *Methods Inf Med* 2006, **45**:409–413.
154. Bland JM, Altman DG: **Applying the right statistics: analyses of measurement studies.** *Ultrasound Obstet Gynecol* 2003, **22**:85–93.

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